Parallel Jacobi Transformation Algorithm for Generalized Eigen-Solution With Improved Damage Detection of Truss/Bridge-Type Structures

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PARALLEL JACOBI TRANSFORMATION ALGORITHM FOR GENERALIZED EIGEN-SOLUTION WITH

IMPROVED DAMAGE DETECTION OF TRUSS/BRIDGE-TYPE STRUCTURES

by

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A Dissertation Submitted to the Faculty of
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Yunbyeong Chae (Member)
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Serial Jacobi transformation algorithm for the solution of “standard eigen-problems” is re-visited to facilitate the explanation of the proposed parallel transformation algorithm, for which computational efficiency can be realized in this study through “pattern recognition” for the development and explanation of “explicit formulas” to avoid costly matrix time matrix operations. The proposed parallel Jacobi transformation for the solution of “generalized eigen-problems” has also been incorporated into the “improved damage detection” algorithm. Computational efficiency and robust behaviors for the entire proposed procedures (eigen-solution, damage detection and damage quantification) can be validated through several academic and real-life numerical examples. Numerical results obtained from this study have indicated that our proposed generalized Jacobi transformation is more robust/reliable as compared to MATLAB eigen-solver. Furthermore, our proposed simple rule of thumb for damage detection of aging bridge structures also give better results than existing algorithms.
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This thesis is dedicated to the proposition
that the harder you work, the luckier you get.
ACKNOWLEDGMENTS

There are a lot of people who contributed to this dissertation. First, I would like to thank my committee members, whose precious guidance and comments improved the quality of this manuscript. I would like to express my appreciation to my major advisor, Professor Nguyen, who devoted his precious time and knowledge guiding me and walking along with me through this journey; I highly appreciate his tireless efforts and devotion. Furthermore, I do thank my friends who were by my side during my program and this dissertation. Finally, I would like to thank my family, who has been my greatest support all my life. I devote this work to my father and mother, who sacrificed their lives to create mine in the best way possible, also to my sister, whose support and energy have been my greatest strengths.
NOMENCLATURE

\( K \)  Stiffness Matrix
\( M \)  Mass Matrix
\( \lambda \)  Eigen-Value Matrix
\( \phi \)  Eigen-Vector Matrix
\( P_i \)  Rotation or Transformation Matrix
\( \omega \)  Frequency Matrix
\( \bar{F}_D \)  Flexibility Matrix
\( E_l^{(e)} \)  Strain Energy
\( K_R \)  Reduced Stiffness Matrix
\( M_R \)  Reduced Mass Matrix
\( d_L^{(e)} \)  Local element displacement
\( d_G^{(e)} \)  Global element displacement
\( \bar{E}^{(e)} \)  Normalized Cumulative Energy
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CHAPTER 1

INTRODUCTION

During the past decades, substantial research efforts have been devoted to the development of damage identification techniques for civil engineering structures with both simulation and experimental studies. Based on the comprehensive literature reviews [1–3], vibration-based damage identification (VBDI) approaches have been widely developed and become an important research topic in the fields of civil, mechanical and aerospace engineering. Model-based techniques, a class of VBDI approaches, can be utilized effectively for both damage localization and quantification. In the techniques, an analytical or a numerical model (e.g. finite element methods) is generally required to give eigen-solutions of the monitored structure. As a result, performing eigen analysis with computational efficiency becomes one of the important factors affecting the effectiveness of this kind of model-based techniques.

For an undamped vibrating structure with N degrees-of-freedoms, the “generalized eigen-problem” [4-8] can be described by the following equation:

\[ K_{N \times N} \phi = \lambda M_{N \times N} \phi \]  

(1)

For solving the above “generalized” eigen-problem, efficient solutions, such as Subspace Iteration [4, 7], Lanczos algorithms [4, 6-8] have been well documented in the literature. It should also be
mentioned that if the above NxN “Mass” matrix [M] becomes an Identity matrix [I], then the above “generalized” eigen-problem will be simplified to the “standard” eigen-problem:

\[ K_{N \times N} \phi = \lambda \phi \]  

In Eqs. (1-2), K, \( \lambda \) and \( \phi \) represent the system “stiffness,” “eigen-values” and “eigen-vectors” matrices, respectively. The Jacobi transformation/rotation family of algorithms [4-8] basically transforms the standard/generalized eigen-problem into diagonal matrix for easily computing all eigen-pairs.

1.1 Literature Surveys

Many researchers [4, 6-8] have considered the classical Jacobi rotation algorithm to transform the symmetrical, “standard eigen-problem” into diagonal matrix with all eigen-values appeared on its diagonal locations. Sameh and other researchers have extended the above classical (Jacobi rotation) procedure into “parallel Jacobi” algorithm [9] by simply demanding several (instead of only one) off-diagonal terms be driven to zero in each transformation. In Sameh’s prior work [9], however, all eigen-pairs of the “standard eigen-problem” need to be computed.

Bathe and other researchers have incorporated the classical Jacobi transformation into the subspace iteration algorithm [4] so that only the first few (or all) eigen-pairs can be found for the
“generalized eigen-problem.” Using the subspace iteration algorithm, the “sparse” matrix operations can be easily exploited [4, 7, 10]. However, in Bathe’s prior works [4], only one (not multiple) off-diagonal term at a time can be driven to zero.

1.2 Goals for This Study

The goals and objectives for this work are not only to extend the capability of the “stand-alone, generalized eigen-solver” [as shown in Table 1], but also to incorporate the parallel generalized eigen-solver into practical (real-life) engineering applications such as structural health monitoring. In this present work, first, the Jacobi transformation algorithm is embedded inside the subspace iteration algorithm to calculate the generalized eigen-problem of the monitored structure.

To provide the effective computational procedure, a parallel computing strategy based on the idea of making several off-diagonal terms to be simultaneously driven to zero is used for the Jacobi transformation algorithm, which is called parallel subspace iteration and Jacobi transformation (PSI-JT) algorithm. Then, the PSI-JT algorithm is incorporated into a two-phase damage identification method to improving the quality of damage assessment results in terms of the accurate solution and computational time.
Finally, 2-D and 3-D truss/bridge-type structures are presented to validate the superior performance of the proposed damage identification approach.

|                       | Standard Eigen-Problem | Generalized Eigen-Problem | Parallel Computation** | All Eigen-Pairs | Few Lowest Eigen-Pairs | Sparse | Dense |
|-----------------------|------------------------|---------------------------|------------------------|-----------------|------------------------|--------|
| Sameh’s early works   | Yes                    | No                        | Yes                    | Yes             | No                     | No     | Yes   |
| K.J. Bathe’s early works | Yes                  | Yes                       | No                     | Yes             | Yes                    | Some   | Yes   |
| This dissertation/work | Yes                    | Yes                       | Yes                    | Yes             | Yes                    | Yes    | Yes   |

** Several (not just one) off-diagonal terms can be driven to zero in each transformation

The remaining sections of this dissertation will be organized as follows. After the introduction section, the classical Jacobi transformation for the solution of the “generalized eigen-problem” is briefly reviewed in Section 2.1. Next, in Section 2.2, explicit formulas (based on observed pattern recognitions) for the triple products (matrix times matrix) operations are developed and explained. Parallel computing strategies are presented in Section 2.3, for which Sameh’s prior publications will be presented in a fashion such that the “explicit formulas” developed in Section
2.2 can be fully incorporated. Subspace iteration algorithm is summarized in Section 2.4, so that only “few lowest eigen-pairs” specified by the user can be computed for the “generalized eigen-problem.” Section 2.4 also shows that the stand-alone “Jacobi transformation” algorithm (presented in Sections 2.2, and 2.3) are embedded inside the subspace iteration algorithm. In Section 2.5, the superior performance (in terms of reduction in wall-clock time) of the parallel PSI-JT algorithm is investigated by comparing to the well-established MATLAB built-in eigen-solver such as the EIG function.

Existing damage detection and damage quantification are discussed in Section 3.1 and 3.2, for which a “simple rule of thumb” is proposed in section 3.1 to improve the quality of damage detection in bridge structures. Additional several numerical examples are presented in Section 3.3 to validate our claim for “improving the quality of damage detection” as compared to recently published algorithms. Finally, conclusion and future research works are highlighted in Section 4.

1.3 Assumptions for This Study

The following assumptions are made in this work:

Assumption 1: Damage can be imposed on the structure by specifying the level of damage (in percentage) occurred in certain members (not occurred in certain joints). For example, if member #5 of a 2-D truss structure is damaged by 30 % (or 0.30), then every term of the 4x4 element stiffness matrix of the damage member
#5 can be computed based on the original (undamage) member #5 element stiffness matrix, to be multiplied by the adjustment factor 0.70 ( = 1.00 – 0.30 ).

Assumption 2: For practical applications, the few sensor-locations should be placed at certain optimal locations (or at certain optimal degree-of-freedoms). Only the frequencies and mode-shapes (or eigen-vectors) at these sensor-locations are measured, while the information on system stiffness and mass matrices of the damage structure are unavailable. Thus, in this work we have assumed that the L x L eigen-vectors of the damage structure at the sensor-locations can be converted (or transformed) into the “full” N x L eigen-vectors (where L << N) through any existing model reduction methods (such as Guyan reduction method, Dynamic reduction method, etc.), which utilize the available information on the original (undamage) system stiffness and mass matrices.
In the well-documented (classical) Jacobi transformation method, the original “stiffness” matrix \([K]\) and “mass” matrix \([M]\) in Eq. (1) can be repeatedly transformed into diagonal matrices, \([K^*]\) and \([M^*]\) respectively, through the Jacobi transformation as shown in Eqs. (3-4)

\[
[K_{N \times N}] [\phi] = [\lambda] [M_{N \times N}] [\phi]; \quad K \text{ and } M \text{ are symmetrical.} \tag{Eq. 1, repeated}
\]

\[
K^* = P_1^T K P_1 \tag{3}
\]

\[
M^* = P_1^T M P_1 \tag{4}
\]

and the rotation (or transformation) matrix \([P_1]\) can be defined as:

\[
P_1^T = \begin{bmatrix}
1 & \theta_1 & 0 & 0 \\
\theta_2 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \tag{5}
\]

In Eq. (5), we have assumed that the new off-diagonal terms for matrix \(K^*\) at location \((p, q) = (1, 2)\) to be driven to zero through the transformation shown in Eqs. (3-4). \(\theta_1\) and \(\theta_2\) are the 2 unknowns, which can be solved by applying the following equations:
\( K_{12}^* = 0, \text{ and } M_{12}^* = 0 \) \hspace{1cm} (6)

2.1. A Review of Jacobi Transformation for The Solution of the “Generalized Eigen-Problem”

The following derivation is valid, when \( k_{12} \) is intended to become zero. For the general case, two unknowns should be placed in \( k_{ij} \) and \( k_{ji} \) locations.

\[
K^* = P_1^T K P_1
\]

\[
= \begin{bmatrix} 1 & \theta_1 & 0 & 0 \\ \theta_2 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} \\ k_{21} & k_{22} & k_{23} & k_{24} \\ k_{31} & k_{32} & k_{33} & k_{34} \\ k_{41} & k_{42} & k_{43} & k_{44} \end{bmatrix} \begin{bmatrix} 1 & \theta_2 & 0 & 0 \\ \theta_1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\]

\[
= \begin{bmatrix} k_{11} + k_{12}\theta_1 & k_{11}\theta_2 + k_{12} & k_{13} & k_{14} \\ k_{21} + k_{22}\theta_1 & k_{21}\theta_2 + k_{22} & k_{23} & k_{24} \\ k_{31} + k_{32}\theta_1 & k_{31}\theta_2 + k_{32} & k_{33} & k_{34} \\ k_{41} + k_{42}\theta_1 & k_{41}\theta_2 + k_{42} & k_{43} & k_{44} \end{bmatrix}
\]

After performing the triple products shown in Eq. (8), \( K^* \) is obtained as it is represented in equation (9).

\[
K^* =
\]
\begin{align*}
(k_{11} + k_{12} \theta_1) + \theta_1 (k_{21} + k_{22} \theta_1) & \quad (k_{11} \theta_2 + k_{12}) + \theta_1 (k_{21} \theta_2 + k_{22}) \\
\text{sym.} & \quad \theta_2 (k_{11} \theta_2 + k_{12}) + (k_{21} \theta_2 + k_{22}) \\
\text{sym.} & \quad \theta_2 (k_{11} \theta_2 + k_{12}) \\
\text{sym.} & \quad \theta_2 k_1 + k_2 \\
\text{sym.} & \quad \theta_2 k_1 + k_2 \\
\text{sym.} & \quad \theta_2 k_1 + k_2 \\
\text{sym.} & \quad \theta_2 k_1 + k_2 \\
k_{13} + \theta_1 k_2 & \quad k_{14} + \theta_1 k_{24} \\
k_{33} & \quad k_{34} \\
k_{44} & \\
\end{align*}

Thus, \( K_{1,2}^* = 0 = (k_{11} \theta_2 + k_{12}) + \theta_1 (k_{21} \theta_2 + k_{22}) \) \hspace{1cm} (10)

\[M_{1,2}^* = 0 = (M_{11} \theta_2 + M_{12}) + \theta_1 (M_{21} \theta_2 + M_{22})\] \hspace{1cm} (11)

From Eqs. (10) & (11):

\[
\theta_1 = \frac{-(k_{11} \theta_2 + k_{12})}{(k_{21} \theta_2 + k_{22})} = \frac{-(M_{11} \theta_2 + M_{12})}{(M_{21} \theta_2 + M_{22})} \hspace{1cm} (12)
\]

Hence \( \theta_2 \) can be computed from equation (12), as shown in the following paragraph.

From Eq. (12), one obtains:

\[(k_{11} \theta_2 + k_{12}) (M_{21} \theta_2 + M_{22}) = (k_{21} \theta_2 + k_{22}) (M_{11} \theta_2 + M_{12})\] \hspace{1cm} (13)
The above Eq. (14) can be expressed as:

\[
(A_1) \theta_2^2 + (B_1) \theta_2 + (C_1) = 0
\]  

(15)

Hence,

\[
\theta_2 = \frac{-B_1 \pm \sqrt{B_1^2 - 4A_1C_1}}{2A_1} \quad \text{(assuming } A_1 \neq 0) \tag{16}
\]

In Eq. (16), if the denominator \( A_1 = 0 \); then from (Eq. (15), one obtains:

\[
\theta_2 = \frac{-C_1}{B_1}
\]  

(17)

Finally, \( \theta_1 \) can be found from Eq. (12)

The sign in front of the SQRT of Eq. (16) will be based on the sign of \( \bar{k} \), defined as below.
\[
\bar{k} = B_1 = (k_{11}M_{22} + k_{12}M_{21} - k_{21}M_{12} - k_{22}M_{11})
\]  

Equation (18)

After computing \( \theta_2 \) [see Eq. (16), or Eq. (17)], and \( \theta_1 \) [see Eq. (12)], matrix \( P_1^T \) can be generated as shown below:

\[
P_1^T = \begin{bmatrix}
1 & \theta_1 & 0 & 0 \\
\theta_2 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

Equation (19)

In the following steps, “explicit formulas” for the modified / transformed matrix \( K^* \) and \( M^* \) should be developed (\( K^* = P_1^T K P_1, \) and \( M^* = P_1^T M P_1 \)). In the transformed matrix \( K^* \) and \( M^* \), it is assumed the selected off-diagonal terms (\( k_{12} = k_{21}, \) and \( m_{12} = m_{21} \)) should be driven to zero.

The above procedure will be repeated until all the off-diagonal terms become zero. Equation 20 shows this procedure [4].

\[
P_N^T \ldots P_2^T P_1^T K P_1 \ldots P_N = K^*
\]

Equation (20)

In Eq. (20), the matrix \( K^* \) eventually becomes a diagonal (eigen-value) matrix, where \( N \) is the size of \( K_{N \times N} \). Furthermore, Eigen-Vectors matrix can also be identified from Eq. (20) [4, 7]:
Based on Ref. [9], more than one off-diagonal terms can be driven to zero, which will also be adopted in this work.

The most time-consuming part of the Jacobi Rotation procedure is the computation, which involves with repeated matrix times matrix operations.

\[
\begin{align*}
P_1 P_2 \ldots P_N &= \phi \\
P_N^T \ldots P_2^T P_1^T K P_1 P_2 \ldots P_N
\end{align*}
\]  

In this work, however, expensive matrix times matrix operations can be avoided by recognizing the pattern of “explicit formulas” for \( P_{i+1}^T K P_{i+1} \), which will be explained in greater details in the next section.

### 2.2 Development of “Explicit Formulas” For Triple Matrix Times Matrix Operations

We have observed that there are specific patterns in the result of \( K^* = P_1^T K P_1 \) [see Eq. (9)], which will be repeated in every step of the procedure.
First of all, it is observed that the changes in matrix $K^*$ (as compared to matrix $K$) only happens in the terms associated with the related rows and columns of matrix $K$ ($i^{th}$ row and $j^{th}$ column for the selected $K_{ij}$, which will become zero, after the Jacobi transformation step $K^* = P_1^T K P_1$ is completed).

For better explanation, assuming that $K_{12}$ [or $K_{pq}$, where $p=1$, and $q=2$] is selected to become zero after the Jacobi transformation. For the pairs ($p$, $q$), it can be defined:

- The “companion” row for “row $p$” is “row $q$,” and the “companion” row for “row $q$” is “row $p$.”
- The “companion” column for “column $p$” is “column $q$,” and the “companion” column for “column $q$” is “column $p$.”

Recalled Eqs. (7-8), $P_1$ can be defined as:

$$P_1 = \begin{bmatrix}
1 & \theta_2 & 0 & 0 \\
\theta_1 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(22)

Matrix $K^*$ can be computed as follows, based on Eqs. (3, 4, 9).
\[
\begin{align*}
(k_{11} + k_{12} \theta_1) + \theta_1 (k_{21} + k_{22} \theta_1) & \quad (k_{11} \theta_2 + k_{12}) + \theta_1 (k_{21} \theta_2 + k_{22}) \quad k_{13} + \theta_1 k_{23} \quad k_{14} + \theta_1 k_{24} \\
\text{sym.} & \quad \theta_2 (k_{11} \theta_2 + k_{12}) + (k_{21} \theta_2 + k_{22}) \quad \theta_2 k_{13} + k_{23} \quad \theta_2 k_{14} + k_{24} \\
\text{sym.} & \quad \text{sym.} \quad k_{33} \quad k_{34} \\
\text{sym.} & \quad \text{sym.} \quad \text{sym.} \quad k_{44}
\end{align*}
\]

In general, it has been observed that the transformation of all the components of \( K \) matrix, can be categorized in 3 different types. In other words, each of the components of matrix \( K \) will be transformed based on one of these three types.

These three types or categories are observed to be dependent on the location of the component in the transformed matrix \( K_{ij}^* \) as shown in Eq. (9). It is also observed that the developed formula is independent of the location of selected \( K_{ij} \) (selected component to become zero). The “explicit” formulas for each term \( K_{ij}^* \) can be developed based on the observed patterns, as described in the following paragraphs.

1. **Type 1**: All \( K_{ij} \) terms, which none of the indexes are either \( p=1 \) or \( q=2 \) (such as \( K_{33}, K_{34} \) and \( K_{44} \)). In other words, all terms \( K_{ij}^* \) for which \( i \neq p, q, \) and \( j \neq q, p \)
These (type 1) terms will not change after the triple product matrix multiplications \( K^* = P_1^T K P_1 \) and their values remain the same.

2. **Type 2**: All \( K_{ij} \) terms, which only one of the indexes are either \( p=1 \) or \( q=2 \) (such as \( K_{13}, K_{14}, K_{23}, \) and \( K_{24} \)). In other words, all terms \( K_{ij}^* \) for which \( i = \) either \( p \), or \( q \) and \( j \neq p \) and \( j \neq q \).

These \( K_{ij}^* \) terms can be computed based on the following “explicit” formula:

\[
K_{ij}^* = K_{ij} + \theta_m K \text{ ("companion" row for "row i," j)}
\] (23)

The subscript \( m \) of \( \theta \) can be found by looking at the “companion” row for “row i” of the rotation matrix \( P_1 \). Based on the “explicit” formula shown in Eq. (23), we can compute:

\[
K_{13}^* = K_{13} + \theta_m K \text{ ("companion" row for "row 1," 3)}
\]

\[
K_{13}^* = K_{13} + \theta_m K_{23}
\] (24)

Where the subscript \( m \) of \( \theta \) can be found by looking at the “companion” row for “row i = 1” of the rotation matrix \( P_1 \). In this case, “companion” row for “row i = 1” is row 2 (by referring to \( p=1 \) and \( q=2 \)). Thus, by looking at row 2 of matrix \( P_1 \), it can be easily identified that \( \theta_m = \theta_1 \). Hence,
\[ K_{13}^* = K_{13} + \theta_1^* K_{23} \]  

(25)

Similarly, we can compute:

\[ K_{24}^* = K_{24} + \theta_m^* K \]  

(“companion” row for “row 2,” 4)

(26)

where the subscript \( m \) of \( \theta \) can be found by looking at the “companion” row for “row \( i = 2 \)” of the rotation matrix \( P_1 \). In this case, “companion” row for “row \( i = 2 \)” is row 1. Thus, by looking at row 1 of matrix \( P_1 \), it can be easily identified that \( \theta_m = \theta_2 \). Hence,

\[ K_{24}^* = K_{24} + \theta_2^* K_{14} \]  

(27)

3. **Type 3**: All \( K_{ij} \) terms, for which both indices are either \( p=1 \) or \( q=2 \) (such as \( K_{11}, K_{12} \) and \( K_{22} \)).

In other words, all terms \( K_{ij}^* \) for which \( i = \) either \( p \), or \( q \) and \( j = \) either \( p \), or \( q \).

These \( K_{ij}^* \) terms can be computed based on the following 2 steps:
Step 3.1: In this step, the “exact, same” procedure as explained in Type 2 is followed. For example,

\[ K_{12}^* = K_{12} + \theta_m \times K \text{ (“companion” row for “row 1,” 2)} \]

\[ K_{12}^* = K_{12}^{\wedge\wedge} + \theta_m \times K_{22}^{\wedge\wedge} \]  

(28)

Then, referring to row 2 of matrix \( P_1 \), the proper subscript \( m \) for theta is obtained, hence

\[ K_{12}^* = K_{12}^{\wedge\wedge} + \theta_1 \times K_{22}^{\wedge\wedge} \]  

(29)

Step 3.2: In this step \( K_{12}^{\wedge\wedge} \), shown in Eq. (29), is replaced by the following formulas:

\[ K_{12}^{\wedge\wedge} = K_{12} + \theta_r \times K \text{ (“companion” column for “column 2”)} \]  

(30)

\[ K_{12}^{\wedge\wedge} = K_{12} + \theta_r \times K_{11} \]

where, the subscript “r” of \( \theta \) can be obtained by referring to column 1 of matrix \( P_1^T \). Thus,
Similarly, Replacing $K_{(2,2)^\wedge}$, shown in Eq. (29), by the following formulas:

$$K_{22}^\wedge = K_{22} + \theta_s * K_{21}$$  \hspace{1cm} (33)$$

where, the subscript “s” of $\theta$ can be obtained by referring to column 1 of matrix $P_1^T$.

Thus:

$$K_{22}^\wedge = K_{22} + \theta_s * K_{21}$$  \hspace{1cm} (34)$$

Finally, substituting Eqs. (31, 34) into Eq. (29), one obtains

$$K_{12}^* = \{ K_{12} + \theta_2 * K_{11} \} + \theta_1 * \{ K_{22} + \theta_2 * K_{21} \}$$  \hspace{1cm} (35)$$

Similar procedures can be used to compute $K_{11}^*$, and $K_{22}^*$ for these type 3 terms of matrix $[K^*]$. 

$$K_{12}^\wedge = K_{12} + \theta_2 * K_{11}$$  \hspace{1cm} (31)$$
2.3 Parallel Computing Strategies for Jacobi Transformation Algorithm

Sameh presented an algorithm [9] that can zero-out several off-diagonal terms (row “p,” column “q”) simultaneously, for the “Standard NxN Eigen-Problem.” This idea can also be applied for the “Generalized NxN Eigen-Problem,” where p and q are sequences defined by Sameh [9], in which p & q can be swapped, so that p is less than q. The complete algorithm (to systematically identify all the off-diagonal locations (p, q) of matrix [K]) driven by Sameh is presented in his early work in detail [9] and can be conveniently summarized here, as follows:

a) For k = 1, 2, ..., m-1 [where m = n / 2; and k = step #]

\[ q = m - k + 1, m - k + 2, \ldots, n - k, \]
\[ p = (2m - 2k + 1) - q, \quad \text{if} \quad m - k + 1 \leq q \leq 2m - 2k \]
\[ p = (4m - 2k) - q, \quad \text{if} \quad 2m - 2k < q \leq 2m - k - 1 \]
\[ p = n, \quad \text{if} \quad 2m - k - 1 < q \]

b) For k = m, m+1, ..., 2m-1

\[ q = 4m - n - k, 4m - n - k + 1, \ldots, 3m - k - 1, \]
\[ p = n, \quad \text{if} \quad q < 2m - k + 1 \]
\[ p = (4m - 2k) - q, \quad \text{if} \quad 2m - k + 1 \leq q \leq 4m - 2k - 1 \]
\[ p = (6m - 2k - 1) - q, \quad \text{if} \quad 4m - 2k - 1 < q \]
**Example 1:** For a 4x4 matrix \([K]\); \(n = 4\); \(k = \text{step } # = 1, 2, ..., n-1 = 3\);

For each step \(m = n/2 = 2\) off-diagonal terms are simultaneously driven to zero. Applying the above algorithm, the following steps are produced:

- step #1: \((p, q) = (1,2) & (3,4)\)
- step #2: \((p, q) = (2,4) & (1,3)\)
- step #3: \((p, q) = (1,4) & (2,3)\)

**Example 2:** For a 6x6 matrix \([K]\); \(n = 6\); \(k = \text{step } # = 1, 2, ..., n-1 = 5 \ F\)

or each step \(m = n/2 = 3\) off-diagonal terms are simultaneously driven to zero. Applying the above algorithm the pairs are as below:

- step #1: \((p, q) = (2,3), (1,4) & (5,6)\)
- step #2: \((p, q) = (1,2), (3,5) & (4,6)\)
- step #3: \((p, q) = (3,6), (2,4) & (1,5)\)
- step #4: \((p, q) = (2,6), (1,3) & (4,5)\)
- step #5: \((p, q) = (1,6), (2,5) & (3,4)\)

Extension of Ref. [9] for Parallel Jacobi Transformation of “Generalized Eigen-Problems” is described in the following part of this section.

The generalized eigen-equations, see Eq. (1), can be re-stated as
\[
[K_{N \times N}] [\phi] = [\lambda] [M_{N \times N}][\phi]
\]  
(36)

In eq (36), \( K \) is a Symmetrical Positive Definite (SPD) “stiffness” matrix.

\[
K^* = P_1^T K P_1
\]  
(3, repeated)

\[
M^* = P_1^T M P_1
\]  
(4, repeated)

Assuming the off-diagonal terms of matrix \( K^* \) and \( M^* \), at locations \((p, q) = (1, 2) \) & \((p, q) = (3, 4)\), are intended to be driven to zero. Thus,

\[
P_1^T = \begin{bmatrix}
1 & \theta_1 & 0 & 0 \\
\theta_2 & 1 & 0 & 0 \\
0 & 0 & 1 & \theta_3 \\
0 & 0 & \theta_4 & 1
\end{bmatrix}
\]  
(37)

The 4 unknowns \( \theta_1, \theta_2, \theta_3 \) and \( \theta_4 \) can be solved by employing 4 associated equations \( K_{12}^* = 0 = K_{34}^* = M_{12}^* = M_{34}^* \), and using similar “explicit formulas” developed in Section 2.1 of this dissertation.

2.4 Subspace Iteration
Subspace Iteration and Lanczos Algorithms [4-8] have been used extensively in the engineering communities for solving the generalized eigen-problem

\[ K_{N \times N} \phi = \lambda M_{N \times N} \phi \]  

(36, repeated)

The details of “Subspace Iteration” algorithm is presented in the following step-by-step procedure:

Step 1: Guess \([X_k]_{N \times L}\), where \(L \ll N\) and \(L \approx (2 \text{ to } 4) \times (\# \text{ lowest Eigen Pairs desired})\)

Step 2: The following equation is developed

\[ [K] \bar{X}_{k+1} = [M] X_k \]  

(38)

The unknown, \([\bar{X}_{k+1}]\), can be solved by sparse equation solver [6-8, 10], where \(K\) and \(M\) are sparse (SPD = Symmetric Positive Definite) matrices.

Step 3: Reduced problem is created in this step by applying the result from previous step to original stiffness and mass matrices. The following “reduced” stiffness and “reduced” mass matrices are obtained:
Step 4: Solve for all eigen-pairs of the Generalized (Dense) Reduced Eigen-Problem [see Jacobi transformation with explicit formulas in Section 2.2]:

\[
[K_{Reduce}]_{L \times L} = [X_{k+1}^T]_{N \times N} [K]_{N \times N} [X_{k+1}]_{N \times L}
\] (39)

\[
[M_{Reduce}]_{L \times L} = [X_{k+1}^T]_{L \times N} [M]_{N \times N} [X_{k+1}]_{N \times L}
\]

Step 5: In this step the guessed (eigen-vector) matrix \([X]\) is being update using equation (41).

\[
[X_{k+1}]_{N \times L} = [\bar{X}_{k+1}]_{N \times L} \times [E\_Vectors]_{L \times L}
\] (41)

If the algorithm converges, then the subspace iteration process stops, if the algorithm is not converged, then, returns to Step 2, and replaces \(X_k\) by \(X_{k+1}\). This procedure will continue until the convergence achieved [4].

2.5 Numerical Examples for Subspace Iteration with Jacobi Rotation (PSI-JT) for Eigen-Problems
In this section, several illustrative test examples are used to evaluate the performance of the proposed PSI-JT algorithm, in both MATLAB sequential and parallel computing environments. The results for eigen-solutions, and wall-clock time are reported in Tables 2-5.

All the examples are real world eigen value problems, which shows the PSI-JT algorithm super performance in comparison with MATLAB built-in function.

Table 2. 2003 x 2003 Size Fluid Flow eig Solution Time and Solution Accuracy

<table>
<thead>
<tr>
<th>Requested Eigenvalue</th>
<th>PSI-JT algorithm</th>
<th>MATLAB “eig”</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.449043</td>
<td>2.458226</td>
</tr>
<tr>
<td></td>
<td>(9 subspace iteration)</td>
<td>(9 subspace iteration)</td>
</tr>
<tr>
<td>4</td>
<td>2.742210</td>
<td>2.454659</td>
</tr>
<tr>
<td></td>
<td>(8 subspace iteration)</td>
<td>(8 subspace iteration)</td>
</tr>
<tr>
<td>10</td>
<td>6.689142</td>
<td>Not converged</td>
</tr>
<tr>
<td></td>
<td>(8 subspace iteration)</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>102.968629</td>
<td>Not converged</td>
</tr>
<tr>
<td></td>
<td>(8 subspace iteration)</td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>2027.442472</td>
<td>Not converged</td>
</tr>
<tr>
<td></td>
<td>(7 subspace iteration)</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. **1086 x 1086 Size Buckling of Hot Washer eig Solution Time and Solution Accuracy**

<table>
<thead>
<tr>
<th>Requested Eigenvalue</th>
<th>PSI-JT algorithm</th>
<th>MATLAB “eig”</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.916372 (9 subspace iteration)</td>
<td>1.650959 (27 subspace iteration)</td>
</tr>
<tr>
<td>4</td>
<td>2.348291 (11 subspace iteration)</td>
<td>1.449550 (20 subspace iteration)</td>
</tr>
<tr>
<td>10</td>
<td>5.795341 (8 subspace iteration)</td>
<td>Not converged</td>
</tr>
<tr>
<td>27</td>
<td>98.628914 (8 subspace iteration)</td>
<td>Not converged</td>
</tr>
<tr>
<td>63</td>
<td>2016.937281 (7 subspace iteration)</td>
<td>Not converged</td>
</tr>
</tbody>
</table>

Table 4. **420 x 420 Size Lumped Mass eig Solution Time and Solution Accuracy**

<table>
<thead>
<tr>
<th>Requested Eigenvalue</th>
<th>PSI-JT algorithm</th>
<th>MATLAB “eig”</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.199795 (9 subspace iteration)</td>
<td>0.092030 (11 subspace iteration)</td>
</tr>
<tr>
<td>4</td>
<td>0.376640 (7 subspace iteration)</td>
<td>0.091801 (7 subspace iteration)</td>
</tr>
<tr>
<td>10</td>
<td>4.459468 (7 subspace iteration)</td>
<td>Not converged</td>
</tr>
<tr>
<td>20</td>
<td>1405.341492 (7 subspace iteration)</td>
<td>Not converged</td>
</tr>
</tbody>
</table>
To follow, a different number of eigen-pairs for a specific problem is requested. The parallel performance and time comparison for this example using different number of processors are represented in Tables 6-9. This example is a real-world fluid flow eigen-value problem, in which the stiffness matrix is a module of an offshore platform [Refs. 23]. The stiffness matrix has exactly 3948 rows and 3948 columns. It is a sparse, symmetric positive definite matrix that is a structural full rank matrix. A high number of components makes it time consuming for non-parallel algorithms to solve and order the eigen-pairs of such matrix. However, by using the proposed algorithm a few numbers of eigen-pairs can be found in a reasonable amount of time.
Table 6. Fluid Flow Generalized Eigenvalues, Symmetric Stiffness Matrix, First 66 Eigen-Pairs

<table>
<thead>
<tr>
<th>Requested Eigenvalue</th>
<th>Entire subspace iteration 1 processor time (sec)</th>
<th>Entire subspace iteration 2 processor time (sec)</th>
<th>Entire subspace iteration 3 processor time (sec)</th>
<th>Entire subspace iteration 4 processor time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>66</td>
<td>896.455950</td>
<td>1102.822512</td>
<td>1261.48776</td>
<td>895.840537</td>
</tr>
<tr>
<td></td>
<td>1101.811450</td>
<td>1260.467577</td>
<td>895.378442</td>
<td>1260.467577</td>
</tr>
<tr>
<td></td>
<td>895.840537</td>
<td>894.852254</td>
<td>590.352192</td>
<td>422.939288</td>
</tr>
<tr>
<td></td>
<td>590.352192</td>
<td>589.355626</td>
<td>421.939288</td>
<td>421.939288</td>
</tr>
<tr>
<td>Average</td>
<td>861.6497</td>
<td>860.6341</td>
<td>578.2087</td>
<td>518.9749</td>
</tr>
<tr>
<td>Speed Ratio</td>
<td>1</td>
<td>1.491027</td>
<td>1.5212</td>
<td>1.658337</td>
</tr>
<tr>
<td>Efficiency</td>
<td>100%</td>
<td>74.5%</td>
<td>50.7%</td>
<td>41.4%</td>
</tr>
</tbody>
</table>

Table 7. Fluid Flow Generalized Eigenvalues, Symmetric Stiffness Matrix, First 77 Eigen-Pairs

<table>
<thead>
<tr>
<th>Requested Eigenvalue</th>
<th>Entire subspace iteration 1 processor time (sec)</th>
<th>Entire subspace iteration 2 processor time (sec)</th>
<th>Entire subspace iteration 3 processor time (sec)</th>
<th>Entire subspace iteration 4 processor time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>77</td>
<td>831.959080</td>
<td>1051.925227</td>
<td>1048.577007</td>
<td>743.936809</td>
</tr>
<tr>
<td></td>
<td>1050.620045</td>
<td>1047.274977</td>
<td>742.619260</td>
<td>523.077149</td>
</tr>
<tr>
<td></td>
<td>830.658220</td>
<td>846.129932</td>
<td>607.145950</td>
<td>436.999096</td>
</tr>
<tr>
<td></td>
<td>713.84270</td>
<td>863.853816</td>
<td>605.873926</td>
<td>393.059580</td>
</tr>
<tr>
<td>Average</td>
<td>718.5048</td>
<td>596.5495</td>
<td>334.649933</td>
<td>293.608608</td>
</tr>
<tr>
<td>Speed Ratio</td>
<td>1</td>
<td>1.204934</td>
<td>1.242526</td>
<td>1.363352</td>
</tr>
<tr>
<td>Efficiency</td>
<td>100%</td>
<td>60%</td>
<td>41.4%</td>
<td>34%</td>
</tr>
</tbody>
</table>
### Table 8. Fluid Flow Generalized Eigenvalues, Symmetric Stiffness Matrix, First 100 Eigen-Pairs

<table>
<thead>
<tr>
<th>Requested Eigenvalue</th>
<th>Entire subspace iteration 1 processor time (sec)</th>
<th>Entire subspace iteration 2 processor time (sec)</th>
<th>Entire subspace iteration 3 processor time (sec)</th>
<th>Entire subspace iteration 4 processor time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 processor</td>
<td>2 processor</td>
<td>3 processors</td>
<td>4 processors</td>
</tr>
<tr>
<td>100</td>
<td>1788.015892</td>
<td>1182.113598</td>
<td>1089.22413</td>
<td>1087.59278</td>
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<tr>
<td></td>
<td>2186.397163</td>
<td>1480.840859</td>
<td>1304.322926</td>
<td>1302.711819</td>
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<td></td>
<td>2010.273289</td>
<td>1362.213095</td>
<td>1320.355531</td>
<td>1318.70545</td>
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<td></td>
<td>1749.809894</td>
<td>1143.397802</td>
<td>1056.207567</td>
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<td></td>
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<td></td>
<td>801.335118</td>
<td>630.311019</td>
<td>679.719767</td>
<td>678.119807</td>
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<tr>
<td></td>
<td>631.880441</td>
<td>515.988933</td>
<td>571.278204</td>
<td>569.617665</td>
</tr>
<tr>
<td>Average</td>
<td>1537.942</td>
<td>1017.924</td>
<td>980.2771</td>
<td>978.6503</td>
</tr>
<tr>
<td>Speed Ratio</td>
<td>1</td>
<td>1.51158</td>
<td>1.569855</td>
<td>1.651394</td>
</tr>
<tr>
<td>Efficiency</td>
<td>100%</td>
<td>75%</td>
<td>52%</td>
<td>41%</td>
</tr>
</tbody>
</table>

### Table 9. Fluid Flow Generalized Eigenvalues, Symmetric Stiffness Matrix, First 130 Eigen-Pairs

<table>
<thead>
<tr>
<th>Requested Eigenvalue</th>
<th>Entire subspace iteration 1 processor time (sec)</th>
<th>Entire subspace iteration 2 processor time (sec)</th>
<th>Entire subspace iteration 3 processor time (sec)</th>
<th>Entire subspace iteration 4 processor time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 processor</td>
<td>2 processor</td>
<td>3 processors</td>
<td>4 processors</td>
</tr>
<tr>
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<td>2912.711002</td>
<td>2976.439071</td>
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<td>3292.546426</td>
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<tr>
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<td>2456.850108</td>
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<td>1631.485206</td>
<td>2006.354640</td>
</tr>
<tr>
<td></td>
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<td>1482.917552</td>
<td>1480.925914</td>
<td>1656.405730</td>
</tr>
<tr>
<td></td>
<td>2136.548267</td>
<td>1360.015900</td>
<td>1358.008694</td>
<td>1519.861581</td>
</tr>
<tr>
<td>Average</td>
<td>3839.152</td>
<td>2416.479</td>
<td>2414.464</td>
<td>2385.03</td>
</tr>
<tr>
<td>Speed Ratio</td>
<td>1</td>
<td>1.589223</td>
<td>1.610207</td>
<td>1.722739</td>
</tr>
<tr>
<td>Efficiency</td>
<td>100%</td>
<td>79.5%</td>
<td>53.6%</td>
<td>43%</td>
</tr>
</tbody>
</table>
Damage detection in structures, specifically bridge type structures, is an important subject. Due to its important application in real world problems, this topic attracts a lot of old and new scholars to research on this topic. A lot of researchers have investigated damage detection or health monitoring problems and presented methods [11-18].

In this chapter, a two-phase method is presented for damage detection using a “simple rule of thumb” for structural damage detection and quantification. The merit of the present two-phase method over other existing two-phase methods [13,14] is that a simple but efficient “rule of thumb” is proposed for the improvement in damage detection, together with the parallel PSI-JT algorithm that is incorporated to effectively compute for the generalized eigen-problem.

Figure 1. A 6-Node, 11-Member Two-Dimensional Truss Structure
To illustrate damage localization and quantification process of the two-phase method, an example of a 2-D Truss/Bridge Structure, shown in Figure 1, is used herein. In Figure 1, the lengths of each member, the cross-sectional area of each member, the material density and Youngs modulus are user’s input parameters. In general, the Finite Element Method (FEM) will be based on the type of structure we wish to analyze. This illustrative example is based on a 2-D Truss/Bridge type structure. Using FEM, a structure can be analyzed under (a) undamaged (original) condition, and (b) damaged condition.

Once the frequencies (related to eigen-values) & mode-shapes (eigen-vectors) of the damage structure is measured (via optimal locations of sensors), the proposed method can robustly detect the “location (Phase ½) and the severity (Phase 2/2)” of damage members. The step-by-step numerical procedures of this two-phase method can be summarized in the following sections.

### 3.1. Phase 1/2: Detect/Identify Damage Members

**Step 1.0 Finite Element Analysis of “Original” (Undamage) Structure**

In this step, first the element stiffness $[k_L^{(e)}]$ matrices, and the element diagonal/lumped mass $[m_L^{(e)}]$ matrices are computed.
Then, the global stiffness $[K] = \sum[k_{G}^{(e)}]$ matrix, and the global $[M] = \sum[m_{G}^{(e)}]$ diagonal/ lumped mass matrix is assembled. Using MATLAB command equation (42) is driven.

$$[\phi, \lambda] = EIG(K_{bc}, M_{bc}) \tag{42}$$

Then, the Eigen Values ($[\lambda]$ and frequencies, $\omega_i$) can be obtained, and the corresponding Eigen Vectors (mode-shapes $\phi_i$) can be identified through the matrix $[\phi]$. MATLAB “EIG” command will solve the “generalized” eigen-equation:

$$[K_{bc}]\phi_i^* = \omega_i^2 [M_{bc}] \phi_i^* \tag{43}$$

Next, the mass-orthonormalized scalar of each eigen vector is computed.

$$\{\phi_i^*\}^T [M_{bc}] \{\phi_i^*\} = \text{scalar} = c_i \tag{44}$$

$$\{\phi_i\} = \frac{\{\phi_i^*\}}{\sqrt{c_i}} \tag{45}$$

Thus,

$$\tilde{F}_{UD} = \tilde{F}_{Undamaged} = \sum_{i=1}^{NLM} \frac{1}{\omega_i} \phi_i \phi_i^T \text{; where NLM = Number of Lowest Modes} \tag{46}$$
**Step 2.0 (very similar to Step 1.0)**

Using FEM, the associated damaged structure is also analyzed. In real life structure, the measurements of frequencies & mode shapes would come from sensors installed on the structure at key locations. For our example, “artificial damage” is applied to elements #1, #5 and #10 of the mentioned example [see Figure 1], with stiffness reduction of 80%, 70% and 90% for those 3 elements, respectively.

In this step, it would be desirable to compute the element stiffness matrices $[k^{(e)}_L]$ with damage members. However, the element mass $[m^{(e)}_L]$ diagonal matrices with no damage applied is required to be used.

Next, the global damaged stiffness $[K] = \sum [k^{(e)}_G]$, and the global $[M] = \sum [m^{(e)}_G]$ diagonal lumped mass matrices are assembled respectively. Then, boundary conditions are applied on the system’s stiffness and mass matrices $[K_{bc}]$ and $[M_{bc}]$, respectively. Using the MATLAB command represents in equation (47) the eigen pairs are obtained.

$$[\phi, \lambda] = EIG(K_{bc}, M_{bc})$$  \hspace{1cm} (47)

Then, the Eigen Values ([$\lambda$] and frequencies $\omega_i$) is obtained. The corresponding Eigen Vectors (mode- shapes $\phi_i$) can be identified by the matrix $[\phi]$. MATLAB command EIG will solve the “generalized” eigen-equation represented in eq (48).
\[ [K_{bc}]_D \phi_i^* = \omega_i^2 [M_{bc}] \phi_i^* \] (48)

**Remarks:** After obtaining the eigen-solution for damage structure, it is pretended that the damage members and their severities are unknown.

Then, the Mass-Orthonormalized scalar of each eigen vector is computed.

\[ \{\phi_i^*\}^T [M_{bc}] \{\phi_i^*\} = \text{scalar} = c_i \] (49)

\[ \{\phi_i\} = \frac{\{\phi_i^*\}}{\sqrt{c_i}} \quad \text{Thus,} \] (50)

\[ F_D = F_{\text{Damaged}} = \sum_{i=1}^{NLM} \frac{1}{\omega_i^2} \phi_i \phi_i^T \] (51)

\[ \bar{F}_\Delta = \bar{F}_{UD} - \bar{F}_D \] (52)

\[ [U,S,V] = SVD(\bar{F}_\Delta) \] (53)

Then by using MATLAB “SVD” command, which is represented in eq (53), the given matrix [see Eq. (52)] into its triple products is decomposed, where the second (or middle) matrix is a diagonal matrix, and the first & third matrices are ORTHOGONAL matrices:

\[ F_\Delta = [U][\varepsilon][V]^T \] (54)
\[
[U_1 \quad U_0][\varepsilon_1 \quad [0] \quad [V_1 \quad V_0]]^T
\] (55)

“If the column vectors in the matrix \([V_0]\) are treated like different loading conditions/vectors [19, 20], then the stresses of damage elements will be equal to zero.” In practical application, we should use “Strain Energy” \(E_{(e)}^i\), instead of stress associated with each \(e^{th}\) element, and check for low strain elements [13-14].

\[
E_{(e)}^i = \frac{1}{2} \{d_L^{(e)}\}^T [k_L^{(e)}] d_L^{(e)} = \text{scalar};
\] (56)

where \(i = 1,2,3,...\) ndlv = number of damaged location vectors = \# of columns of the sub-matrix \([V_0]\).

Notes: the above elements’ strain energy is associated with the “original (undamage)” structure, since the goal of Phase 1 is to find and identify “which members are damaged.”

\[
\{d_L^{(e)}\} = [R^{(e)}] d_g^{(e)}
\] (57)

where:

\[
[R^{(e)}] = \begin{bmatrix}
C_x & S_x & 0 & 0 \\
-S_x & C_x & 0 & 0 \\
0 & 0 & C_x & S_x \\
0 & 0 & -S_x & C_x
\end{bmatrix}; \text{and } C_x = \frac{x_j-x_i}{L^{(e)}} ; \ C_y = \frac{y_j-y_i}{L^{(e)}}
\] (58)
\[ L^{(e)} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} \]  \hspace{1cm} (59)

Instead of using Stress, or Strain Energy for each element, we use the “Normalized Cumulative Energy,” or “NCE” for each element \([21,22]\), which is defined as

\[ \bar{E}^{(e)} = \frac{\psi^{(e)}}{\max_k \{\psi^k\}} \]  \hspace{1cm} (60)

where, \( \psi^{(e)} = \sum_{i=1}^{n_i} \frac{E_i^{(e)}}{\max_k \{E_i^k\}} \) \hspace{1cm} (61)

For each \( e^{th} \) element (corresponding to the \( i^{th} \) loading case), \( E_i^{(e)} \) is computed as shown above for the undamage case. Within each \( i^{th} \) loading case, the max value among all elements “e” is found and the \( \max_k \{E_i^k\} \) is obtained. Then, Eq. (61) is applied to compute \( \psi^{(e)} \).

Among all \( \psi^{(e)} \) values computed, the max value = \( \max_k \{\psi^k\} \) is found and Eq. (60) is applied to compute “NCE” \( \equiv \bar{E}^{(e)} \). Based on the computed “NCE” = \( \bar{E}^{(e)} \), eq (62) is obtained.
Notice that $\tilde{E}^{(11)}$ is exactly zero. However, element #11 should **NOT** be considered as a damage element, because this element has 2 end nodes which are fully constrained by 2 pinned (Dirichlet boundary condition) supports. This element has its nodal displacements equal to zero, thus it has no stress and has zero “normalized cumulative energy.”

3.2. **Phase 2/2: Determine the Level of Severity for Those Few Damage Members**

Using optimization techniques, such as Genetic Algorithm (GA), or Differential Evolution (DE), etc., one can find the level (or amount) of damage occurred in elements # (1), # (5) and # (10) that have already been found/identified in Phase 1/2.

Let $\tilde{x} = \text{the unknown amount of damage in the truss elements # (1), # (5) and # (10)}$. 

\[
\tilde{E}^{(e)} = \begin{cases} 
\tilde{E}^{(1)}, & \text{very close to zero (even when 3 or 4 lowest modes used)} \\
\tilde{E}^{(2)}, & \text{very close to zero (even when 3 or 4 lowest modes used)} \\
\tilde{E}^{(3)}, & \text{very close to zero (even when 3 or 4 lowest modes used)} \\
\tilde{E}^{(4)}, & \text{very close to zero (even when 3 or 4 lowest modes used)} \\
\tilde{E}^{(5)}, & \text{very close to zero (even when 3 or 4 lowest modes used)} \\
\tilde{E}^{(6)}, & \text{very close to zero (when 6 lowest modes used)} \\
\tilde{E}^{(7)}, & \text{exactly zero (Element #11 is connected by 2 pinned nodes)} \\
\tilde{E}^{(8)}, & \text{exactly zero (Element #11 is connected by 2 pinned nodes)} \\
\tilde{E}^{(9)}, & \text{exactly zero (Element #11 is connected by 2 pinned nodes)} \\
\tilde{E}^{(10)}, & \text{exactly zero (Element #11 is connected by 2 pinned nodes)} \\
\tilde{E}^{(11)}, & \text{exactly zero (Element #11 is connected by 2 pinned nodes)} 
\end{cases}
\]
\[
\tilde{x} = \begin{cases}
  x^{(1)} = [0.00 \rightarrow 1.00] \\
  x^{(2)} = [0.00 \rightarrow 1.00] \\
  x^{(3)} = [0.00 \rightarrow 1.00]
\end{cases}
\]

(63)

Thus, the optimization problem can be stated. The unknown vector \( \tilde{x} \) is found, such that the OBJECTIVE function \( \Gamma(\tilde{x}) \), defined in eq. (64), is minimized [22].

\[
\text{Min. } \Gamma(\tilde{x}) = 1 - MDLAC(\tilde{x}) + \sum_{i=1}^{NLM} \frac{\| \phi_{DM,i} - \phi_{DA,i}(\tilde{x}) \|}{\| \phi_{DM,i} \|}
\]

(64)

In eq. (64), \( \phi_{DM,i} \) = the \( i \)th damaged mode shape, which can be obtained by measurements (using sensors at strategic/optimal locations), in real-life/practical applications.

\( \phi_{DA,i}(\tilde{x}) \) = the \( i \)th analytical (damage) mode shape, associated with the current amount of damage vector \( \tilde{x} \), found by the optimization (GA, or DE, etc...) process. In this dissertation example, the actual measurements have not been taken. Instead, artificially created damage conditions to VALIDATE the numerical procedures.

\[
M DLAC(\tilde{x}) = \frac{|\Delta f^T \delta f(\tilde{x})|^2}{(\Delta f^T \Delta f)(\delta f^T(\tilde{x}) \delta f(\tilde{x}))} \leq 1
\]

(65)

The right-hand side of the above inequality can be easily verified by Cauchy’s inequality, and
\[ \Delta f = \frac{\|\vec{f}_{ud} - \vec{f}_{DM}\|}{\|\vec{f}_{ud}\|} \]  \hspace{1cm} (66) \\

\[ \delta f(\vec{x}) = \frac{\|\vec{f}_{ud} - \vec{f}_{DA}(\vec{x})\|}{\|\vec{f}_{ud}\|} \]  \hspace{1cm} (67) \\

“If \( \vec{f}_{DM} = \vec{f}_{DA}(\vec{x}) \), as the measured frequency vector of the damage structure is equal to the analytical (damage) frequency vector, “Then,” the Eqs. (66-67) will lead to \( \Delta f = \delta f(\vec{x}) \), and Eq. (65) will become \( MDLAC(\vec{x}) = 1 \).

Hence the Minimum value for the objective function will become [see Eq. (64)]:

\[ \text{Min.} \Gamma(\vec{x}) = 1 - [\text{MDLAC}(x) = 1] + \{\text{summation term} = 0\} = 0 \]

In this work, a “simple rule of thumb” has been added for improving damage detection phase. This rule of thumb basically states that “if the Normalized Cumulative Energy of an element is less than or equal to a specific factor, say 10 (based on our numerical experience) times \( \min(\vec{E}(e)) \), then that member should also be considered as a damage element.” However, this “rule of thumb” should obviously NOT be applied for finding the minimum energy for any member with fully constraints at its end nodes, such as member 11 of Figure 1).

\[ E^{(e)} \leq 10 \times \min(\vec{E}(e)) \]  \hspace{1cm} (68)
3.3. Numerical Examples for Damage Detection and Damage Quantification

In this Section, several numerical examples are used to evaluate the performance of the proposed “simple rule of thumb,” which basically modify the existing algorithms for Damage Detection and Damage Quantification of Bridge-type Structures.

Comparisons between existing algorithms [13, 14], and the proposed “simple/inexpensive rule of thumb” are reported in Tables 10, 11 and 13, and in Figures 2-5. All the figures are the last iteration results, which the meaning of each diagram is explained in follow.

In all figures, the upper diagram, X-axes show the “number of variations,” which represents the number of damage elements (for instance, the number of bars shows the number of damage elements), and Y-axes named as “current best individual” show the severity of damage elements for each of the damage members.

In the lower diagram, the X-axis shows “score” that indicates the fitness (objective) function value, and this Y-axis also shows number of populations, which falls within the score ranges.

It is worth mentioning that these figures have been created by MATLAB software automatically and represent the convergence of the problem to the results, which are shown in these figures. In other words, upper figure shows the number of damage members and their damage severities, and the lower figure shows the number of individuals and their respective fitness value range.
(for example, in figure 2, almost 30 individuals in the population has the fitness value in range of 0.2-0.5x10^{-3}). Summation of all bars’ heights in the lower diagram gives the population size generated by MATLAB code.

In this work, different sizes for 2-D and 3-D truss/bridge-type problems have been investigated, using the proposed algorithm. In each example, some elements are considered to be damaged with different levels of severity. It is shown in the following problems that the improved algorithm, can easily recognize the damage elements and their severities (either low or high), regardless of the input amount of severities on damage elements. It is worth mentioning that existing algorithms [13, 14] are unable to detect all of the damage members, especially those with low severity, in some cases, as it is fully described in the related papers [13, 14].
Table 10. 11-bar Truss Examples with Different Damage Elements (Case 1, 2 and 3)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80%</td>
<td>detected</td>
<td>1</td>
<td>20%</td>
<td>Not detected</td>
<td>1</td>
<td>70%</td>
<td>detected</td>
</tr>
<tr>
<td>5</td>
<td>70%</td>
<td>detected</td>
<td>7</td>
<td>10%</td>
<td>Not detected</td>
<td>3</td>
<td>50%</td>
<td>Not detected</td>
</tr>
<tr>
<td>10</td>
<td>90%</td>
<td>detected</td>
<td>5</td>
<td>30%</td>
<td>Not detected</td>
<td>6</td>
<td>70%</td>
<td>detected</td>
</tr>
<tr>
<td>10</td>
<td>50%</td>
<td>detected</td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>20%</td>
<td>Not detected</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9</td>
<td>40%</td>
<td>Not detected</td>
</tr>
</tbody>
</table>

Figure 2. MATLAB Result for 11-bar Truss with 3 Damage Members (1, 5, 10)
Another case that has been studied is a 48-bar 3D truss, which contains 1 bay, 3 stories, and 2 frames. Each frame consists of columns, beams and X braces in each bay and stories, including the connecting bays.
Table 11. 48 Bar Truss Example with 5 Damage Elements (Case 4)

<table>
<thead>
<tr>
<th>Damage Element</th>
<th>Damage Severity</th>
<th>Detected elements by existed alg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>90%</td>
<td>detected</td>
</tr>
<tr>
<td>13</td>
<td>80%</td>
<td>Not detected</td>
</tr>
<tr>
<td>20</td>
<td>60%</td>
<td>Not detected</td>
</tr>
<tr>
<td>35</td>
<td>90%</td>
<td>detected</td>
</tr>
<tr>
<td>37</td>
<td>20%</td>
<td>Not detected</td>
</tr>
</tbody>
</table>

Figure 5. MATLAB Result for 48-bar Truss Damage Members (5, 13, 20, 35, 37)
Another example is a bridge with 10 bays, each 8 feet, 8 stories, each 8 feet and 6 frames, each 8 feet. Each frame consists of columns, beams, and X brace frames. This example is a simply supported has 1782 degrees of freedom, 594 nodes, and 3288 members and is a larger size problem. This structure has been used to show the time efficiency as well as accuracy of the proposed method.

In this example, 5 elements have been identified as damage by the proposed algorithm correctly. The damage severity of members is varied, which have been detected by the program correctly. Also, the computing time is reduced by using 2 processors in parallel computation. Computation time using different number of processors is reported in Table 12. The results can be found in Table 13 and Figure 6.

<table>
<thead>
<tr>
<th>Number of processors</th>
<th>Time (second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1375.4501</td>
</tr>
<tr>
<td>2</td>
<td>941.3579</td>
</tr>
<tr>
<td>3</td>
<td>898.6813</td>
</tr>
<tr>
<td>4</td>
<td>867.9016</td>
</tr>
</tbody>
</table>
Table 13. Larger Scale Truss Example with 5 Damage Elements (Case 5)

<table>
<thead>
<tr>
<th>Damage Element</th>
<th>Damage Severity</th>
<th>Detected elements by existed alg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>80%</td>
<td>detected</td>
</tr>
<tr>
<td>37</td>
<td>70%</td>
<td>Not detected</td>
</tr>
<tr>
<td>55</td>
<td>90%</td>
<td>Not detected</td>
</tr>
<tr>
<td>529</td>
<td>75%</td>
<td>Not detected</td>
</tr>
<tr>
<td>705</td>
<td>40%</td>
<td>Not detected</td>
</tr>
</tbody>
</table>

Figure 6. MATLAB Result for Larger Truss Damage Members (10, 37, 55, 529, 705)
There are some cases in which, even by considering large number of mode-shapes, existing algorithms [13, 14] will not be able to detect “all” damage elements, especially when the number of damage elements is more than 3. Using our suggested “simple rule of thumb,” however, existing algorithms [13, 14] will be able to detect “all” damage members.

Subspace iteration in combination with Jacobi rotation algorithm have been implemented into the damage detection problem for computing the few lowest eigenpairs. Combination of subspace iteration and MATLAB “eig” built-in function have also been used for performance evaluation. In almost all numerical cases considered in this study, this combined (subspace iteration and MATLAB “eig”) algorithm does not converge to the correct eigen-pairs. These mentioned numerical results have clearly shown that our proposed PSI-JT algorithm is more robust (reliable) as compared to MATLAB built-in “EIG” function.
CHAPTER 4
CONCLUSIONS

Serial Jacobi transformation algorithm for the solution of “standard eigen-problems” is re-visited to facilitate the explanation of the proposed parallel transformation algorithm, for which computational efficiency can be realized in this study through “pattern recognition” for the development of “explicit formulas” to avoid costly matrix time matrix operations.

In this work, the Jacobi transformation algorithm is embedded inside the subspace iteration algorithm to calculate the generalized eigen-problem of the monitored structure. To provide the effective computational procedure, a parallel computing strategy based on the idea of making several off-diagonal terms to be simultaneously driven to zero is used for the Jacobi transformation algorithm, which is so-called parallel subspace iteration and Jacobi transformation (PSI-JT) algorithm. The results depict the accuracy and time efficiency of the proposed algorithm.

Numerical results obtained from this study have indicated that our proposed generalized Jacobi transformation is more robust and reliable as compared to MATLAB eigen-solver. Specifically, for obtaining more eigen pairs, the PSI-JT algorithm is shown to produce more robust results.
The proposed parallel Jacobi transformation for the solution of “generalized eigen-problems” has also been incorporated into our “improved damage detection” algorithm. Computational efficiency and robust behavior for the entire proposed procedures (eigen-solution, damage detection and damage quantification) can be validated through several academic and real-life numerical examples.

For damage members severity estimation, an optimization problem needs to be solved repeatedly to converge to the correct solution. Using PSI-JT algorithm is depicted to produce robust solution in damage severity quantification.
REFERENCES


24. https://sparse.tamu.edu/HB
Old Dominion University (ODU) MATLAB Source Code for “Parallel Subspace Iteration with Jacobi Transformation”

A.1 Subspace source code with Jacobi Rotation Combination

Below the MATLAB source code of subspace iteration with Jacobi rotation implementation is represented.

```matlab
clear all
close all
clc

% Define K and M matrices
%A = [5 -4 1 0; -4 6 -4 1; -4 6 -4 0 1 -4 5];
%B = [2 -1 0 0; -1 4 -1 0; 0 -1 4 -1; 0 0 -1 2];
N = load('bcsstk13');
N_1 = N.Problem.A;
A = full(N_1);
```
B=eye(size(A,1));

% Input lowest eigen value desired
L =77;

% Deifine first guess
x_k = zeros(size(A,2),(4*L));

for j = 1:size(A,2)
    for i = 1:(4*L)
        x_k(i,i) = 1;
    end
end

x_k = x_k(1:size(A,2), 1:(4*L));

% Subspace code
max_Abs_error_norm = 1;
ecol = 1;
err = 1;
X_bar = x_k;
m_n=0;

% tic
while max_Abs_error_norm > 10e-7 || ecol > 10e-3
    m_n=m_n+1;
    B_mod = B*X_bar;
\[ \text{X\_bar} = \text{A}\backslash\text{B\_mod}; \]

\[ \text{A\_R} = \text{X\_bar}^{\ast}\text{A}\times\text{X\_bar}; \]

\[ \text{B\_R} = \text{X\_bar}^{\ast}\text{B}\times\text{X\_bar}; \]

[\text{val,phi,sweep}] = \text{eigenpair\_generalized\_Parallel\_2(A\_R,B\_R)};

% sort

[\text{val,ind}] = \text{sort(val)};

\text{phi} = \text{phi}(;\text{ind});

\text{X} = \text{X\_bar}\times\text{phi};

\text{for i=1:(L)}

\quad \text{Abs\_error\_norm}(i) = \text{norm}(\text{A}\times(\text{;i})-\text{val}(i)\times\text{B}\times(\text{;i}));

\text{end}

\text{max\_Abs\_error\_norm} = \text{norm(Abs\_error\_norm)};

\text{X\_bar} = \text{X};

\text{if m\_n}\sim=1

\quad \text{for i=1:L}

\quad \quad \text{ecol\_1}(i) = \text{norm(val(i) - val\_store(i))};

\quad \quad \text{ecol} = \text{norm(ecol\_1)};

\quad \text{end}

\quad \text{val\_store} = \text{val};

\text{else}

\text{end}
val_store = val;

end

%%%%% Check
[vc, vl] = eig(A, B);
sval = sort(abs(val));

for i = 1:L
    decc(i) = vl(i, i) - sval(i);
end

n_decc = norm(decc);

A.2 Subspace source code with MATLAB “EIG” Built-in function

Follow Subspace iteration source code with MATLAB EIG built in function is shown.

clear all

close all
clc

% Define K and M matrices
% A = [5 -4 1 0; -4 6 -4 1; 1 -4 6 -4; 0 1 -4 5];
% B = [2 -1 0 0; -1 4 -1 0; 0 -1 4 -1; 0 0 -1 2];

N = load('bcsstk13');
N_1 = N.Problem.A;

A = full(N_1);

B=eye(size(A,1));

% Input lowest eigen value desired
L = 77;

% Define first guess
x_k = zeros(size(A,2),(4*L));

for j = 1:size(A,2)
    for i = 1:(4*L)
        x_k(i,i) = 1;
    end
end

x_k = x_k(1:size(A,2), 1:(4*L));

% Subspace code
max_Abs_error_norm = 1;
ecol = 1;
err = 1;

X_bar = x_k;

m_n = 0;

% tic
while max_Abs_error_norm > 1e-7 || ecol > 1e-3
    m_n = m_n + 1;
end
\[ B_{\text{mod}} = B \times X_{\text{bar}}; \]

\[ X_{\text{bar}} = A \backslash B_{\text{mod}}; \]

\[ A_{R} = X_{\text{bar}}^\ast A \times X_{\text{bar}}; \]

\[ B_{R} = X_{\text{bar}}^\ast B \times X_{\text{bar}}; \]

\[[\phi, \text{val}] = \text{eig}(A_{R}, B_{R});\]

% sort

\[[\text{val}, \text{ind}] = \text{sort}(\text{abs(diag(val))});\]

\[ \phi = \phi(:, \text{ind}); \]

\[ X = X_{\text{bar}}^\ast \phi; \]

\[ \text{for i=1:(L)} \]

\[ \text{Abs_error_norm(i)} = \text{norm}(A \times X(:,i) - \text{val(i)} \times B \times X(:,i)); \]

\[ \text{end} \]

\[ \text{max_Abs_error_norm} = \text{norm(Abs_error_norm)}; \]

\[ X_{\text{bar}} = X; \]

\[ \text{if m_n} = 1 \]

\[ \text{for i=1:L} \]

\[ ecol_1(i) = \text{norm(val(i) - val_store(i))}; \]

\[ ecol = \text{norm(ecol_1)}; \]

\[ \text{end} \]

\[ \text{val_store} = \text{val}; \]

\[ \text{else} \]

\[ \text{end} \]
val_store = val;
end

%%%%%% Check
[vc, vl] = eig(A, B);
sval = sort(abs(val));
for i = 1:L
    decc(i) = vl(i, i) - sval(i);
end
n_decc = norm(decc);

A.3  Jacobi Rotation Source Code

Jacobi rotation source code using the explicit formula described in the previous chapters is presented.

function [val, phi, sweep] = eigenpair_generalized_Parallel_2(k, M)
    n = size(k, 2);
    m = (n + 1)/2;
    m = fix(m);
n_processor = n/2;
    phi = eye(size(k, 1));
nn = 1;
sweep = 0;

while nn ~= 0
    nn = 0;
sweep = sweep + 1;

for rr = 1:size(k,1) - 1
    if rr <= m - 1
        for i = 1:nprocessor
            q(i) = m - rr + i;

            if q(i) <= (2*m - 2*rr) && q(i) >= (m - rr + 1)
                p(i) = (2*m - 2*rr + 1) - q(i);
            elseif q(i) <= (2*m - 2*rr - 1) && q(i) > (2*m - 2*rr)
                p(i) = (4*m - 2*rr) - q(i);
            elseif q(i) > (2*m - rr - 1)
                p(i) = n;
            end

            if q(i) < p(i)
                pc = p(i);
                p(i) = q(i);
                q(i) = pc;
            end
        end
    end
end
elseif \( rr \geq m \)

    for \( i = 1:n\text{processor} \)

        \% if \( k = (2*m-1) \) \&\& \( i = 2 \)
        \%
        \% \( q(i) = 3*m - k - 1; \)
        \%
        \% else
        \%
        \% \( q(i) = 4*m - n - rr + i - 1; \)
        \%
        \% end

        if \( q(i) > (4*m - 2*rr - 1) \)

            \( p(i) = (6*m - 2*rr - 1) - q(i); \)

        elseif \( q(i) \geq (2*m - rr + 1) \) \&\& \( q(i) \leq (4*m - 2*rr - 1) \)

            \( p(i) = (4*m - 2*rr) - q(i); \)

        elseif \( q(i) < (2*m - rr + 1) \)

            \( p(i) = n; \)

        end

        if \( q(i) < p(i) \)

            \( pc = p(i); \)

            \( p(i) = q(i); \)

            \( q(i) = pc; \)

        end

    end

end
% p1=zeros(size(k));
% for i=1:size(k,1)
%     p1(i,i)=1;
% end
p1=eye(size(k));

kbar = zeros(size(k,1));
k_bar = zeros(1,size(p,2));
x = zeros(1,size(p,2));
lambda = zeros(1,size(p,2));
alpha = zeros(1,size(p,2));

for i = 1:size(p,2)
    if (k(p(i),p(i))/M(p(i),p(i)))==(k(q(i),q(i))/M(q(i),q(i)))==(k(p(i),q(i))/M(p(i),q(i)))
        alpha(i) = 0;
        lambda(i) = (-1)*(k(p(i),q(i))/k(q(i),q(i)));
    else
        kbar(p(i),p(i)) = k(p(i),p(i))*M(p(i),q(i)) - M(p(i),p(i))*k(p(i),q(i));
        kbar(q(i),q(i)) = k(q(i),q(i))*M(p(i),q(i)) - M(q(i),q(i))*k(p(i),q(i));
        k_bar(i) = k(p(i),p(i))*M(q(i),q(i)) - k(q(i),q(i))*M(p(i),p(i));
        if k_bar(i)>=0
            x(i) = (k_bar(i)/2)+sqrt((k_bar(i)/2)^2+kbar(p(i),p(i))*kbar(q(i),q(i)));
        elseif k_bar(i)<0
            x(i) = (k_bar(i)/2)-sqrt((k_bar(i)/2)^2+kbar(p(i),p(i))*kbar(q(i),q(i)));
    end
end
\[
\lambda(i) = (\frac{-1}{x(i)}) \times \frac{k_{bar}(p(i), p(i))}{x(i)};
\]
\[
\alpha(i) = \frac{k_{bar}(q(i), q(i))}{x(i)};
\]
\[
p_1(p(i), q(i)) = \alpha(i);
\]
\[
p_1(q(i), p(i)) = \lambda(i);
\]
\[
\phi = \phi \times p_1;
\]

%%% Creat new k based on my formula

parfor pi=1:nprocessor
    Tempo1 = zeros(p(pi),1);
    Tempo1_M = zeros(p(pi),1);
    Tempo2 = zeros(q(pi),1);
    Tempo2_M = zeros(q(pi),1);
    pSubs = zeros(p(pi),2); %new
    qSubs = zeros(q(pi),2);
    for irow = 1:p(pi)
        [xx,inside_angle] = find(irow==[p;q]);
        Tempo1(irow) = [(xx-1)*alpha(inside_angle)+(2-xx)]* ...
\[ k(p(\text{inside\_angle}),p(\pi))+\lambda(\pi)k(p(\text{inside\_angle}),q(\pi)) \] + ...

\[ (2-xx)\lambda(\text{inside\_angle})+(xx-1)]* ... \]

\[ k(q(\text{inside\_angle}),p(\pi))+\lambda(\pi)k(q(\text{inside\_angle}),q(\pi)) \);

\text{Tempo1\_M}(irow) = [(xx-1)\alpha(\text{inside\_angle})+(2-xx)]* ...

\[ M(p(\text{inside\_angle}),p(\pi))+\lambda(\pi)M(p(\text{inside\_angle}),q(\pi)) \] + ...

\[ (2-xx)\lambda(\text{inside\_angle})+(xx-1)]* ... \]

\[ M(q(\text{inside\_angle}),p(\pi))+\lambda(\pi)M(q(\text{inside\_angle}),q(\pi)) \];

\text{pSubs}(irow,:)=[irow,p(\pi)];  \%new

end

for irow = 1:q(\pi)

\[ xx,\text{inside\_angle}] = \text{find}(irow==[p;q]); \]

\text{Tempo2}(irow) = [(xx-1)\alpha(\text{inside\_angle})+(2-xx)]* ...

\[ \alpha(\pi)k(p(\text{inside\_angle}),p(\pi))+k(p(\text{inside\_angle}),q(\pi)) \] + ...

\[ (2-xx)\lambda(\text{inside\_angle})+(xx-1)]* ... \]

\[ \alpha(\pi)k(q(\text{inside\_angle}),p(\pi))+k(q(\text{inside\_angle}),q(\pi)) \];

\text{Tempo2\_M}(irow) = [(xx-1)\alpha(\text{inside\_angle})+(2-xx)]* ...

\[ \alpha(\pi)M(p(\text{inside\_angle}),p(\pi))+M(p(\text{inside\_angle}),q(\pi)) \] + ...

\[ (2-xx)\lambda(\text{inside\_angle})+(xx-1)]* ... \]

\[ \alpha(\pi)M(q(\text{inside\_angle}),p(\pi))+M(q(\text{inside\_angle}),q(\pi)) \];

\text{qSubs}(irow,:)=[irow,q(\pi)];  \%new

end
subsCell{pi,1}=[pSubs;qSubs]; %new

kValCell{pi,1}=[Tempo1;Tempo2];

MValCell{pi,1}=[Tempo1_M;Tempo2_M];

%Assign tempos to k
%   for irow = 1:p(pi)
%       k_1(irow,p(pi)) = Tempo1(irow);
%       k_1(p(pi),irow) = Tempo1(irow);
%       M_1(irow,p(pi)) = Tempo1_M(irow);
%       M_1(p(pi),irow) = Tempo1_M(irow);
%   end

%   for irow = 1:q(pi)
%       k_1(irow,q(pi)) = Tempo2(irow);
%       k_1(q(pi),irow) = Tempo2(irow);
%       M_1(irow,q(pi)) = Tempo2_M(irow);
%       M_1(q(pi),irow) = Tempo2_M(irow);
%   end

subs=cell2mat(subsCell);
kVal=cell2mat(kValCell);
MVal=cell2mat(MValCell);
k_1 = accumarray(subs, kVal, size(k));

M_1 = accumarray(subs, MVal, size(M));

k = k_1 + tril(k_1.',-1); % make symmetric
M = M_1 + tril(M_1.',-1);

end

for ki = 1:size(k,1)
    sum = 0;
    if k(ki,ki) ~= 0
        for kj = 1:size(k,1)
            if kj == ki
                kj = kj + 1;
            else
                sum = sum + abs(k(ki,kj));
            end
        end
    end
    if abs(k(ki,ki)) > (100*sum)
        nn = nn + 0;
    else
        nn = nn + 1;
    end
end
for i = 1:size(k,1)
    val(i)=k(i,i)/M(i,i);
end
APPENDIX 2

One of the examples is a 2003x2003 matrix (a Symmetrical Stiffness Matrix, which represents the Fluid Flow Generalized Eigen-Problems), is also included. If the number of requested eigen-pairs is 63, then MATLAB built-in function (EIG) will not be able to converge to the correct solution.

However, if we replace MATLAB built-in function (EIG) with our Generalized Subspace Iteration with Jacobi Rotation source code, then correct eigen-solutions have been obtained.

The input file has been downloaded from Texas A&M website, and also have been adopted and published in other valid websites described in the related references [23, 24]. Following are the complete information and figures of matrices selected from these sources [23, 24] and used in this dissertation work.

B.1 Symmetrical stiffness matrix, module of an offshore platform

This example is a real-world symmetric stiffness matrix, shows module of an offshore platform. The figure is shown in Figure 7. Matrix properties consist of number of rows and columns, number of nonzero terms and other related features, are represented in the Table 14.
Figure 7. Symmetric Stiffness Matrix, Module of an Offshore Platform

Table 14. Symmetric Stiffness Matrix, Module of an Offshore Platform, Properties

<table>
<thead>
<tr>
<th>Matrix Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of rows</td>
<td>3,948</td>
</tr>
<tr>
<td>number of columns</td>
<td>3,948</td>
</tr>
<tr>
<td>nonzeros</td>
<td>117,816</td>
</tr>
<tr>
<td>structural full rank?</td>
<td>yes</td>
</tr>
<tr>
<td>structural rank</td>
<td>3,948</td>
</tr>
<tr>
<td>explicit zero entries</td>
<td>0</td>
</tr>
<tr>
<td>nonzero pattern symmetry</td>
<td>symmetric</td>
</tr>
<tr>
<td>numeric value symmetry</td>
<td>symmetric</td>
</tr>
<tr>
<td>type</td>
<td>real</td>
</tr>
<tr>
<td>structure</td>
<td>symmetric</td>
</tr>
<tr>
<td>Cholesky candidate?</td>
<td>yes</td>
</tr>
<tr>
<td>positive definite?</td>
<td>yes</td>
</tr>
</tbody>
</table>
This matrix is authored by M. Will, and is edited by I. Duff, R. Grimes, J. Lewis [23]. This matrix is a fluid matrix, and as it is shown in Figure 7, the matrix is related to the 3D problem.

**B.2 Symmetric Stiffness Matrix, Fluid Flow Generalized Eigenvalues**

This example is also a real-world symmetric stiffness matrix, extracted from fluid Flow Generalized Eigenvalues problem. The figure of the matrix is represented in Figure 8, and the matrix properties are described in Table 15.

This matrix is authored by J. Lewis, and is edited by I. Duff, R. Grimes, J. Lewis [23]. This matrix is a computational fluid dynamic 3D problem.

![Figure 8. Symmetric Stiffness Matrix, Fluid Flow Generalized Eigenvalues](image-url)
Table 15. Symmetric Stiffness Matrix, Fluid Flow Generalized Eigenvalues, Properties

<table>
<thead>
<tr>
<th>Matrix Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>number of rows</td>
<td>2,003</td>
</tr>
<tr>
<td>number of columns</td>
<td>2,003</td>
</tr>
<tr>
<td>nonzeros</td>
<td>83,883</td>
</tr>
<tr>
<td>structural full rank?</td>
<td>yes</td>
</tr>
<tr>
<td>structural rank</td>
<td>2,003</td>
</tr>
<tr>
<td>explicit zero entries</td>
<td>0</td>
</tr>
<tr>
<td>nonzero pattern symmetry</td>
<td>symmetric</td>
</tr>
<tr>
<td>numeric value symmetry</td>
<td>symmetric</td>
</tr>
<tr>
<td>type</td>
<td>real</td>
</tr>
<tr>
<td>structure</td>
<td>symmetric</td>
</tr>
<tr>
<td>Cholesky candidate?</td>
<td>yes</td>
</tr>
<tr>
<td>positive definite?</td>
<td>yes</td>
</tr>
</tbody>
</table>

B.3 Symmetric Stiffness Matrix, Buckling of Hot Washer

Another real-world problem is presented in this section. The data is extracted from the websites mentioned in the previous sections [23, 24]. Table 16 shows the properties of this matrix, and Figure 9 demonstrates the figure of the matrix.
This matrix is authored by J. Lewis, and is edited by I. Duff, R. Grimes, J. Lewis [23]. As it is clear from the name of the name, this is matrix is extracted from a structural 3D problem.

![Image of matrix](image.png)

Figure 9. Symmetric Stiffness Matrix, Buckling of Hot Washer

### B.4 Symmetric Stiffness Matrix, Medium Test Problem, Lumped Masses

This is also another structural 3D problem with lower number of rows and columns compare to the previous cases. This matrix is authored by J. Lewis, and is edited by I. Duff, R. Grimes, J. Lewis [23].

More information about matrix properties is described in Table 17, and the figure of the matrix is shown in Figure 10.
Table 16. Symmetric Stiffness Matrix, Buckling of Hot Washer, Properties

<table>
<thead>
<tr>
<th>Matrix Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>number of rows</td>
<td>1,086</td>
</tr>
<tr>
<td>number of columns</td>
<td>1,086</td>
</tr>
<tr>
<td>nonzeros</td>
<td>22,070</td>
</tr>
<tr>
<td>structural full rank?</td>
<td>yes</td>
</tr>
<tr>
<td>structural rank</td>
<td>1,086</td>
</tr>
<tr>
<td>explicit zero entries</td>
<td>0</td>
</tr>
<tr>
<td>nonzero pattern symmetry</td>
<td>symmetric</td>
</tr>
<tr>
<td>numeric value symmetry</td>
<td>symmetric</td>
</tr>
<tr>
<td>type</td>
<td>real</td>
</tr>
<tr>
<td>structure</td>
<td>symmetric</td>
</tr>
<tr>
<td>Cholesky candidate?</td>
<td>yes</td>
</tr>
<tr>
<td>positive definite?</td>
<td>yes</td>
</tr>
</tbody>
</table>
Figure 10. Symmetric Stiffness Matrix, Medium Test Problem, Lumped Masses

Table 17. Symmetric Stiffness Matrix, Medium Test Problem, Lumped Masses, Properties

<table>
<thead>
<tr>
<th>Matrix Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of rows</td>
<td>420</td>
</tr>
<tr>
<td>number of columns</td>
<td>420</td>
</tr>
<tr>
<td>nonzeros</td>
<td>7,860</td>
</tr>
<tr>
<td>structural full rank?</td>
<td>yes</td>
</tr>
<tr>
<td>structural rank</td>
<td>420</td>
</tr>
<tr>
<td>explicit zero entries</td>
<td>0</td>
</tr>
<tr>
<td>nonzero pattern symmetry</td>
<td>symmetric</td>
</tr>
<tr>
<td>numeric value symmetry</td>
<td>symmetric</td>
</tr>
<tr>
<td>type</td>
<td>real</td>
</tr>
<tr>
<td>structure</td>
<td>symmetric</td>
</tr>
<tr>
<td>Cholesky candidate?</td>
<td>yes</td>
</tr>
<tr>
<td>positive definite?</td>
<td>yes</td>
</tr>
</tbody>
</table>
B.5 Symmetric Stiffness Matrix, Transformation Tower, Lumped Masses

This symmetric stiffness matrix is related to a 3D structural problem. It is authored by J. Lewis, and is edited by I. Duff, R. Grimes, J. Lewis [23]. It is worth mentioning that this matrix is one of the small size matrices that has been used in this research for authorizing PSI-JT algorithm.

The figure of this matrix is shown in Figure 11. The properties of the matrix is described in detail in Table 18.

Figure 11. Symmetric Stiffness Matrix, Transformation Tower, Lumped Masses
Table 18. Symmetric Stiffness Matrix, Transformation Tower, Lumped Masses, Properties

<table>
<thead>
<tr>
<th>Matrix Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>number of rows</td>
<td>153</td>
</tr>
<tr>
<td>number of columns</td>
<td>153</td>
</tr>
<tr>
<td>nonzeros</td>
<td>2,423</td>
</tr>
<tr>
<td>structural full rank?</td>
<td>yes</td>
</tr>
<tr>
<td>structural rank</td>
<td>153</td>
</tr>
<tr>
<td>explicit zero entries</td>
<td>0</td>
</tr>
<tr>
<td>nonzero pattern symmetry</td>
<td>symmetric</td>
</tr>
<tr>
<td>numeric value symmetry</td>
<td>symmetric</td>
</tr>
<tr>
<td>type</td>
<td>real</td>
</tr>
<tr>
<td>structure</td>
<td>symmetric</td>
</tr>
<tr>
<td>Cholesky candidate?</td>
<td>yes</td>
</tr>
<tr>
<td>positive definite?</td>
<td>yes</td>
</tr>
</tbody>
</table>

In this research all of the previous cases described in detail in this section, is used to test and validate the performance of PSI-JT algorithm. Looking at the figures of these cases, it is clear that they are completely different in the formation, and are not have a lot in common, but being sparse symmetric positive definite.
APPENDIX 3

Since the code for this section is so large and also Jacobi rotation source code has been presented in Appendix A.3, the complete code for this part will not be mentioned here. However, the Source code for truss generation that has been used to create any size 2D and 3D trusses is presented in this section.

C.1 Truss Creation Source Code

The following source code was written by the dissertation author in MATLAB and is able to create 2D and 3D truss. In this code the user needs to specify very short input data, such as number of bays, number of storied, 2D or 3D format, etc., and the code is able to create the truss and all the features, such as connectivity table, etc., by itself.

```matlab
close all
clear all
clc

% User Inputs
fprintf('n');
nbays=input('ENTER THE NUMBER OF Bays:-');
fprintf('n');
```
fprintf('******************************************************************

% if nbays>=1
fprintf('

Length=input('ENTER THE Length of Each Bay:-');
fprintf('

% end
fprintf('******************************************************************

n')
fprintf('

nstories=input('ENTER THE NUMBER OF Stories:-');
fprintf('

fprintf('******************************************************************

n')
fprintf('

Height=input('ENTER THE Height OF Each Stories:-');
fprintf('

fprintf('******************************************************************

n')
fprintf('

nframes=input('ENTER THE NUMBER OF Frames:-');
fprintf('

fprintf('******************************************************************

n')
fprintf('

Width=input('ENTER THE Width OF Two Consecutive Frames:-');
fprintf('

fprintf('******************************************************************

n');
fprintf('n');
n_node_element=input('ENTER THE NUMBER OF Nodes per Element: -');
fprintf('n');
fprintf('*********************************************************************************************
');
fprintf('n');
% Truss Dimension
global num_dof_node
global num_dof_ele
num_dof_node=input('ENTER THE NUMBER OF SPATIAL DIMENSIONS: -');
um_dof_ele=n_node_element*num_dof_node;
fprintf('n');
fprintf('*********************************************************************************************
');
fprintf('n');
damage_ele=input('ENTER THE damage element and severity [ele sve..]: -');
fprintf('n');
fprintf('*********************************************************************************************
');
fprintf('n');
a_ver=input('ENTER THE Area of Vertical Area: -');
fprintf('n');
fprintf('*********************************************************************************************
');
fprintf('n');
a_hor=input('ENTER THE Area of Horizontal Area: -');
fprintf('n');
fprintf('*********************************************************************************************
');
fprintf('
');
a_diag=input('ENTER THE Area of Diagonal; Area:-');
fprintf('
');

tic

% Compute Number of Nodes
global num_nod
num_nod = (nstories+1)*(nbays+1)*(nframes);
num_nod_fram = (nstories+1)*(nbays+1);

% nodes coordinates
global nod_coor
nod_coor = zeros(num_nod,num_dof_node);
e = 1;
for i = 1:nframes
    for k = 1:nstories+1
        for j = 1:nbays+1
            nod_coor(e,:) = [0+(j-1)*Length, 0+(k-1)*Height, 0+(i-1)*Width];
            e = e+1;
            if e == num_nod+1
                break
            end
        end
    end
end
% Number of Vertical Elements
num_ver_ele = nstories*(nbays+1)*nframes;
num_ver_frame = nstories*(nbays+1);

% Number of Horizontal Elements
num_hor_ele = nstories*nbays*nframes + nstories*(nbays+1)*(nframes-1);

% Number of Diagonal Elements
num_diag_ele = 2*nstories*(2*nbays*nframes+nframes-nbays-1);

%Total Number of Elements
global num_ele
num_ele = num_ver_ele + num_hor_ele + num_diag_ele;

% Construct the Connectivity Matrix
global ele_nod
global A
ele_nod = zeros(num_ele,n_node_element);

% Vertical Elements Connectivity
for j=1:nframes
    for i=(1+num_ver_frame*(j-1)):num_ver_frame*j
        ele_nod(i,:) = [i+(num_nod_fram-num_ver_frame)*(j-1), ...
                       i+(nbays+1)+(num_nod_fram-num_ver_frame)*(j-1)];
        A(i) = a_ver;
    end
end

%Horizontal Elements Connectivity Matrix
[x,y] = find(nod_coor(:,2)~=0);
i = i + 1;
for e = 1:nframes
    for k = 1:nstories
        for j = 1:nbays
            ele_nod(i,:) = [x(j+(k-1)*(nbays+1)+(e-1)*(num_nod_fram-(nbays+1))), ...
                            x(j+1+(k-1)*(nbays+1)+(e-1)*(num_nod_fram-(nbays+1)))];
            A(i) = a_hor;
            i = i + 1;
        end
    end
end

if nframes>1
    for j = 1:((num_nod_fram-(nbays+1))*(nframes-1))
        ele_nod(i,:) = [x(j),x(j)+num_nod_fram];
        A(i) = a_hor;
        i = i+1;
    end
end

%Diagonal Elements Connectivity Matrix
i = i - 1;
for j=1:nbays
    [x1,y1] = find(nod_coor(:,1)==(Length*(j-1)));
    [x2,y2] = find(nod_coor(:,1)==(Length*j));
    sx1 = size(x1,1);
    for e = 1:nframes
for k = 1:((sx1/nframes)-1)
    i = i+1;
    ele_nod(i,:) = [x1(k+((e-1)*(nstories+1))),x2(k+1+((e-1)*(nstories+1)))]
    A(i) = a_diag;
    i = i+1;
    ele_nod(i,:) = [x2(k+((e-1)*(nstories+1))),x1(k+1+((e-1)*(nstories+1)))]
    A(i) = a_diag;
end
end
end

if nframes>1
    for j=1:nbays+1
        [x3,y3] = find(nod_coors(:,1)==(Length*(j-1)));
        sx1 = size(x3,1);
        for e=1:(nframes-1)
            for k = 1:((sx1/nframes)-1)
                i = i+1;
                ele_nod(i,:) = [x3(k+(e-1)*(nstories+1)),x3(k+(e-1)*(nstories+1)+(nstories+2))]
                A(i) = a_diag;
                i = i+1;
                ele_nod(i,:) = [x3(k+(e-1)*(nstories+1)+(nstories+1)), ...
                                x3(k+1+(e-1)*(nstories+1))]
                A(i) = a_diag;
            end
        end
    end
end
% elements degree of freedom (DOF)

global ele_dof

ele_dof = zeros(num_ele,num_dof_ele);

for j=1:num_ele
    ele_dof(j,:)=[((3*ele_nod(j,1))-2),((3*ele_nod(j,1))-1),(3*ele_nod(j,1)), ... 
                   ((3*ele_nod(j,2))-2),((3*ele_nod(j,2))-1),(3*ele_nod(j,2))];
end

% Form Modulus of Elasticity and mass density

global E

for i = 1:num_ele
    E(i) = 30000;
end

global rho

rho = 9.8759999999999994e-3;

fprintf('****************************************************************
*******************************

number_of_loads =input('ENTER THE Number of Loads; Number:');

force = zeros(num_dof_node*num_nod,1);

for j=1:number_of_loads
    node_load_app=input('ENTER THE Node Number that this Load Apply to; Node:');
dof_load_app=input('ENTER THE DOF of the Node that This Load Apply to; DOF:-');
load_value=input('ENTER THE Value of the Applying Load; Value:-');
force((3*node_load_app)-(3-dof_load_app))=load_value;
end
fprintf('
');

%Construct Boundary Condition Vector
displacement=zeros(num_dof_node*num_nod,1);
[x4,y4] = find(nod_coor(:,2)==0);
sx4 = size(x4,1);
global BC
for j=1:sx4
    for k=1:num_dof_node
        BC(k+(3*(j-1)), 1) = (3*x4(j))-(3-k);
    end
end
APPENDIX 4

The input for damage detection & quantification problems comes from both manually (for some examples to check the accuracy of the MATLAB code), and a self-written MATLAB code to generate data such as node coordinates, element nodes, connectivity table of the input truss.

As an example, for 11-bar truss, the input data file that user needs to enter to the computer screen, for using the automatically generated data for truss, is as follows:

- Total number of nodes (6 for this example)
- Number of nodes per element (for this example 2)
- Number of degrees of freedom per node (2 for the example)
- Number of spatial dimension (2 for this example, because it is a 2D truss)
- Number of bays (2 for this example)
- Number of stories (1 for this example)
- Number of frames (0 for this example, since it is a 2D structure)
- Area of each element will be asked and should be input by the user with an enter after inputting each. (For this example: 14, 1, 11, 7, 1, 1, 6, 3, 14, 1, 1)
- Modulus of elasticity (30000 for this example)
- Members’ density (for this example 0.009876)
• Number of applied loads (2 for this example)
• Degree of freedom and magnitude of the applied load ([2,10000] / enter/ [6,10000])

The outputs of sample problems for damage detection & quantification have already described and presented in earlier sections of this dissertation.

The following input is the case when the data is manually inputted. The related input information is as below:

%number of nodes
num_nod=6;
num_dof_node = 3;

% nodes coordinates
nod_coor=[720 0 0;720 360 0;360 0 0;360 360 0;0 0 0;0 360 0];

% connectivity table
ele_nod=[6 4;4 2;5 3;3 1;3 4;1 2;6 3;5 4;4 1;3 2;5 6];

%number of elements
num_ele=size(ele_nod,1);

% elements degree of freedom (DOF)
ele_dof=[16 17 18 10 11 12;10 11 12 4 5 6;13 14 15 7 8 9;7 8 9 1 2 3; ...
7 8 9 10 11 12; 1 2 3 4 5 6;16 17 18 7 8 9;13 14 15 10 11 12; ...
10 11 12 1 2 3;7 8 9 4 5 6;13 14 15 16 17 18];
num_dof_ele = 6;

% A, E, L are cross sectional area, Young’s modulus, length of elements, respectively.
A(1)=14;
A(2)=1;
A(3)=11;
A(4)=7;
A(5)=1;
A(6)=1;
A(7)=6;
A(8)=3;
A(9)=14;
A(10)=1;
A(11)=1;

% E(1)=30000;
for i = 1:num_ele
    E(i) = 30000;
end

rho = 9.8759999999999994e-3;

BC = [1;2;3;4;5;6;25;26;27;28;29;30];

%Define damaged elements and their related severities
damage_ele = [1 0.8;5 0.7;10 0.9];

It is worth mentioning that in the “damage_ele” matrix, mentioned above, the first column shows the damage element number, and the second column shows the damage severity of the related member.

This code is written in MATLAB software. In this case the input properties, such as number of nodes, number of degrees of freedom, etc, are imported by hand for comparison reasons. However, in the bigger size problems, 48-bar truss and 594-bar truss the properties are developed by the “Truss-Creation” Source code, described in the previous sections.
VITA

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