

Some New Upper Bounds for the Spectral Radius of Iterative Matrices

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Abstract—In this paper, we present some new upper bounds for the spectral radius of iterative matrices based on the concept of doubly α diagonally dominant matrix. And subsequently, we give two examples to show that our results are better than the earlier ones.

Keywords—doubly α diagonally dominant matrix, eigenvalue, iterative matrix, spectral radius, upper bound.

I. INTRODUCTION

WE consider the linear system $Ax = b$,

where $A \in C^{n,n}$ is a nonsingular square matrix, and $x, b \in C^n$ with x unknown and b known.

To solve (1), we often split A into $A = M - N$, where M is nonsingular, and apply iterative schemes

$$X^{k+1} = M^{-1}NX^k + d, k = 0, 1, \dots.$$

For example, let

$$A = D - C,$$

Where $D = \text{diag}(A)$, then the associated Jacobi iteration matrix J can be expressed as $J = D^{-1}C$.

Let us denote the class of all complex matrices by $C^{n \times n}$, any eigenvalue by $\lambda(A)$ and the spectral radius of matrix A by $\rho(A)$. And we denote

$$\langle n \rangle = \{1, 2, \dots, n\}, R_i(A) = \sum_{j \neq i} |a_{ij}|,$$

$$S_i(A) = \sum_{i \neq j} |a_{ji}|, P_{i,\alpha}(A) = \alpha P_i(A) + (1 - \alpha)Q_i(A),$$

$i \in \langle n \rangle$.

Definition 1 [1] $A = (a_{ij}) \in C^{n,n}$, then A is called a strictly diagonally dominant matrix and denoted by $A \in D$ if $|a_{ii}| > R_i(A)$, for any $i \in \langle n \rangle$; if

$|a_{ii}| |a_{jj}| > R_i(A)R_j(A)$, for $i, j \in \langle n \rangle, i \neq j$, then A is said to be a doubly diagonally dominant matrix and denoted by $A \in DD$.

Definition 2 [2] if exists an $\alpha \in [0, 1]$, and such that $|a_{ii}| |a_{jj}| > P_{i,\alpha}(A)P_{j,\alpha}(A)$, for $i, j \in \langle n \rangle, i \neq j$, then A is said to be a doubly α diagonally dominant matrix and denoted by $A \in DD(\alpha)$.

As is well known, it is interesting to estimate upper bounds for moduli of eigenvalues or the spectral radius $\rho(M^{-1}N)$ of iteration matrix $M^{-1}N$, and the bound play an important role in many of theoretic analysis (cf.[3,5-10]). In Refs.[3,4,5,6], the following results are presented.

Theorem 1 [3,4] Let $M = (m_{ij}) \in D, N = (n_{ij}) \in C^{n \times n}$. Then

$$|\lambda(M^{-1}N)| \leq \max_{i \in \langle n \rangle} \frac{|n_{ii}| + \sum_{j \neq i} |n_{ij}|}{|m_{ii}| - \sum_{j \neq i} |m_{ij}|}.$$

Theorem 2 [5] Let $M = (m_{ij}) \in DD, N = (n_{ij}) \in C^{n \times n}$. Then

$$|\lambda(M^{-1}N)| \leq \max_{\substack{i \in \langle n \rangle \\ i \neq j}} \frac{B + \sqrt{B^2 - 4AC}}{2A},$$

where

$$A = |m_{ii}m_{jj}| - R_i(M)R_j(M),$$

$$B = |m_{ii}n_{jj}| + |n_{ii}m_{jj}| + R_i(M)R_j(N) + R_i(N)R_j(M),$$

$$C = |n_{ii}n_{jj}| - R_i(N)R_j(N).$$

Theorem 3 [6] Let $M = (m_{ij}) \in DD, N = (n_{ij}) \in C^{n \times n}$. Then

$$|\lambda(M^{-1}N)| \leq \max_{\substack{i \in \langle n \rangle \\ i \neq j}} \frac{B' + \sqrt{B'^2 - 4AC'}}{2A},$$

where

$$A = |m_{ii}m_{jj}| - R_i(M)R_j(M),$$

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$$B' = |m_{ii}n_{jj} + n_{ii}m_{jj}| + R_i(M)R_j(N) + R_i(N)R_j(M),$$

$$C' = -\left[|n_{ii}n_{jj}| + R_i(N)R_j(N)\right].$$

In the following section, we present some new bounds of iteration matrix $M^{-1}N$ when $M \in DD(\alpha)$.

II. MAIN RESULTS

Lemma 1 [2] Let $A = (a_{ij}) \in C^{n \times n}$, if $A \in DD(\alpha)$, then A is a nonsingular matrix.

Lemma 2 [7] Let $A = (a_{ij}) \in C^{n \times n}$, then each eigenvalue of A is included in

$$\bigcup_{i \neq j} \left\{ \lambda \in C : |\lambda - a_{ii}| |\lambda - a_{jj}| \leq R_i(A)R_j(A) \right\}.$$

Theorem 4 Let $M = (m_{ij}) \in DD(\alpha)$, $N = (n_{ij}) \in C^{n \times n}$. Then

$$\left| \rho(M^{-1}N) \right| \leq \max_{\substack{i \in \langle n \rangle \\ i \neq j}} \frac{P_2 + \sqrt{P_2^2 - 4P_1P_3}}{2P_1},$$

where

$$P_1 = |m_{ii}m_{jj}| - P_{i,\alpha}(M)P_{j,\alpha}(M),$$

$$P_2 = |m_{ii}n_{jj}| + |n_{ii}m_{jj}| + P_{i,\alpha}(M)P_{j,\alpha}(N) + P_{i,\alpha}(N)P_{j,\alpha}(M),$$

$$P_3 = |n_{ii}n_{jj}| - P_{i,\alpha}(N)P_{j,\alpha}(N).$$

Proof. Since $M \in DD(\alpha)$, by Lemma 1, we know that M is nonsingular. Without loss of generality, let λ be an arbitrary eigenvalue of $M^{-1}N$, then

$$\det(\lambda I - M^{-1}N) = 0, \text{ i.e.,}$$

$$\det(\lambda M - N) = 0.$$

Moreover if $\lambda M - N \in DD(\alpha)$, by Definition 1 and Lemma 1, we have that

$$|\lambda m_{ii} - n_{ii}| |\lambda m_{jj} - n_{jj}| > P_{i,\alpha}(\lambda M - N)P_{j,\alpha}(\lambda M - N),$$

$$i, j \in \langle n \rangle, i \neq j,$$

then λ is not an eigenvalue of $M^{-1}N$. Especially, if $\left[(|\lambda| |m_{ii}| - |n_{ii}|) (|\lambda| |m_{jj}| - |n_{jj}|) \right] > P_{i,\alpha}(\lambda M - N)P_{j,\alpha}(\lambda M - N)$, $i, j \in \langle n \rangle, i \neq j$,

λ is not an eigenvalue of $M^{-1}N$. Hence by Lemma 2, if λ is an eigenvalue of $M^{-1}N$, then there exists at least a couple of $i, j \in \langle n \rangle (i \neq j)$, such that

$$\left[(|\lambda| |m_{ii}| - |n_{ii}|) (|\lambda| |m_{jj}| - |n_{jj}|) \right] \leq \left[|\lambda| P_{i,\alpha}(M) + P_{i,\alpha}(N) \right] \left[|\lambda| P_{j,\alpha}(M) + P_{j,\alpha}(N) \right],$$

i.e.,

$$\left(|m_{ii}m_{jj}| - P_{i,\alpha}(M)P_{j,\alpha}(M) \right) |\lambda|^2 - \left(|m_{ii}n_{jj}| + |n_{ii}m_{jj}| + P_{i,\alpha}(M)P_{j,\alpha}(N) + P_{i,\alpha}(N)P_{j,\alpha}(M) \right) |\lambda| + |n_{ii}n_{jj}| - P_{i,\alpha}(N)P_{j,\alpha}(N) \leq 0$$

and

$$\left(|m_{ii}m_{jj}| + P_{i,\alpha}(M)P_{j,\alpha}(M) \right) |\lambda|^2 - \left(|m_{ii}n_{jj}| + |n_{ii}m_{jj}| - P_{i,\alpha}(M)P_{j,\alpha}(N) - P_{i,\alpha}(N)P_{j,\alpha}(M) \right) |\lambda| + \left[|n_{ii}n_{jj}| + P_{i,\alpha}(N)P_{j,\alpha}(N) \right] \geq 0$$

For inequality (2): we have

$$P_1 |\lambda|^2 - P_2 |\lambda| + P_3 \leq 0. \tag{4}$$

Since $M \in DD(\alpha)$, $P_1 = |m_{ii}m_{jj}| - P_{i,\alpha}(M)P_{j,\alpha}(M) > 0$ and $P_2 > 0, P_3 > 0$, and the discriminant of a curve of second order $\Delta = P_2^2 - 4P_1P_3 \geq 0$, the solution of (4) satisfies

$$\frac{P_2 - \sqrt{P_2^2 - 4P_1P_3}}{2P_1} \leq |\lambda| \leq \frac{P_2 + \sqrt{P_2^2 - 4P_1P_3}}{2P_1},$$

$i, j \in \langle n \rangle, i \neq j$.

Thus,

$$|\lambda| \leq \frac{P_2 + \sqrt{P_2^2 - 4P_1P_3}}{2P_1}.$$

For inequality (3): Obviously,

$|m_{ii}m_{jj}| + P_{i,\alpha}(M)P_{j,\alpha}(M) > 0$, so we have that the discriminant of a curve of second order $\Delta \leq 0$, solutions of (3) are all complex numbers, i.e., $\lambda \in C$.

Summarizing the above analysis, we get

$$|\lambda| \leq \frac{P_2 + \sqrt{P_2^2 - 4P_1P_3}}{2P_1}.$$

Because λ is an arbitrary eigenvalue of $M^{-1}N$, then

$$\rho(M^{-1}N) \leq \max_{\substack{i, j \in \langle n \rangle \\ i \neq j}} \frac{P_2 + \sqrt{P_2^2 - 4P_1P_3}}{2P_1}.$$

Theorem 5 Let $M = (m_{ij}) \in DD(\alpha)$, $N = (n_{ij}) \in C^{n \times n}$.

Then

$$\left| \rho(M^{-1}N) \right| \leq \max_{\substack{i \in \langle n \rangle \\ i \neq j}} \frac{P_4 + \sqrt{P_4^2 - 4P_1P_5}}{2P_1},$$

where P_1 is the same as in Theorem 4 and

$$P_4 = |m_{ii}n_{jj} + n_{ii}m_{jj}| + P_{i,\alpha}(M)P_{j,\alpha}(N) + P_{i,\alpha}(N)P_{j,\alpha}(M),$$

$$P_5 = -[|n_{ii}n_{jj}| + P_{i,\alpha}(N)P_{j,\alpha}(N)].$$

Proof. Since $M \in DD(\alpha)$, by Lemma 1, we have that M is nonsingular. Without loss of generality, let λ be an arbitrary eigenvalue of $M^{-1}N$, then

$$\det(\lambda I - M^{-1}N) = 0, \text{ i.e.,}$$

$$\det(\lambda M - N) = 0.$$

Moreover, if $\lambda M - N \in DD(\alpha)$, by Definition 1 and Lemma 1, we have that

$$|\lambda m_{ii} - n_{ii}| |\lambda m_{jj} - n_{jj}| > P_{i,\alpha}(\lambda M - N)P_{j,\alpha}(\lambda M - N),$$

$i, j \in \langle n \rangle, i \neq j,$

then λ is not an eigenvalue of $M^{-1}N$. Especially, when $i \neq j$

$$\begin{aligned} & (|m_{ii}m_{jj}|)|\lambda|^2 - (|m_{ii}n_{jj} + n_{ii}m_{jj}|)|\lambda| - |n_{ii}n_{jj}| \\ & > [|\lambda|P_{i,\alpha}(M) + P_{i,\alpha}(N)][|\lambda|P_{j,\alpha}(M) + P_{j,\alpha}(N)], \end{aligned}$$

λ is not an eigenvalue of $M^{-1}N$. When λ is an eigenvalue of $M^{-1}N$, then there exists at least a couple of $i, j \in \langle n \rangle (i \neq j)$, such that

$$\begin{aligned} & (|m_{ii}m_{jj}|)|\lambda|^2 - (|m_{ii}n_{jj} + n_{ii}m_{jj}|)|\lambda| - |n_{ii}n_{jj}| \\ & \leq [|\lambda|P_{i,\alpha}(M) + P_{i,\alpha}(N)][|\lambda|P_{j,\alpha}(M) + P_{j,\alpha}(N)] \end{aligned}$$

i.e.,

$$\begin{aligned} & (|m_{ii}m_{jj}| - P_{i,\alpha}(M)P_{j,\alpha}(M))|\lambda|^2 - (|m_{ii}n_{jj} + n_{ii}m_{jj}| \\ & + P_{i,\alpha}(M)P_{j,\alpha}(N) + P_{i,\alpha}(N)P_{j,\alpha}(M))|\lambda| \\ & - |n_{ii}n_{jj}| - P_{i,\alpha}(N)P_{j,\alpha}(N) \leq 0 \end{aligned}$$

that is,

$$P_1|\lambda|^2 - P_4|\lambda| + P_5 \leq 0. \tag{5}$$

Since $P_1 > 0, P_4 \geq 0$ and $P_5 \leq 0$. and the discriminant of a curve of second order $\Delta = P_4^2 - 4P_1P_5 \geq 0$, the solution of (5) satisfies

$$\frac{P_4 - \sqrt{P_4^2 - 4P_1P_5}}{2P_1} \leq |\lambda| \leq \frac{P_4 + \sqrt{P_4^2 - 4P_1P_5}}{2P_1},$$

$i, j \in \langle n \rangle, i \neq j.$

Thus,

$$\rho(M^{-1}N) \leq \max_{\substack{i \in \langle n \rangle \\ i \neq j}} \frac{P_4 + \sqrt{P_4^2 - 4P_1P_5}}{2P_1}.$$

From Theorem 4 and Theorem 5 we can obtain the following corollary.

Corollary Let $M = (m_{ij}) \in DD(\alpha), N = (n_{ij}) \in C^{n \times n}.$

Then

$$\begin{aligned} & |\rho(M^{-1}N)| \\ & \leq \min \left\{ \max_{\substack{i \in \langle n \rangle \\ i \neq j}} \frac{P_2 + \sqrt{P_2^2 - 4P_1P_3}}{2P_1}, \max_{\substack{i \in \langle n \rangle \\ i \neq j}} \frac{P_4 + \sqrt{P_4^2 - 4P_1P_5}}{2P_1} \right\}, \end{aligned}$$

Where P_1, P_2, P_3, P_4 and P_5 are the same as in Theorem 4 and Theorem 5.

III. EXAMPLES

Examples 1 Let $M = \begin{pmatrix} -3 & 2 & 1 \\ 1 & 3 & 2 \\ 1 & 1 & 4 \end{pmatrix}, N = \begin{pmatrix} 1 & 0 & 3 \\ 0 & 2 & 1 \\ 2 & 0 & 1 \end{pmatrix}.$

Obviously, $M \in DD\left(\frac{1}{2}\right)$, but $M \notin DD$, so we can't

apply Theorem 1, 2 and 3 here. By Theorem 4, we have

$$|\lambda(M^{-1}N)| \leq 10.77.$$

By Theorem 5, we have

$$|\lambda(M^{-1}N)| \leq 7.115.$$

So

$$|\lambda(M^{-1}N)| \leq 7.115.$$

Examples 2 Let $M = \begin{pmatrix} 3 & 2 & 1 \\ 1 & 3 & 2 \\ 1 & 1 & 4 \end{pmatrix}, N = \begin{pmatrix} 1 & 0 & 3 \\ 0 & 2 & 1 \\ 2 & 0 & 1 \end{pmatrix}.$

Obviously, $M \in DD\left(\frac{1}{2}\right)$, but $M \notin DD$, so we can't

apply Theorem 1, 2 and 3 here. By Theorem 4, we have

$$|\lambda(M^{-1}N)| \leq 10.77.$$

By Theorem 5, we have

$$|\lambda(M^{-1}N)| \leq 11.01.$$

So

$$|\lambda(M^{-1}N)| \leq 10.77.$$

Remark: Example 1 shows that Theorem 5 is better than Theorem 4; however, Example 2 shows that Theorem 4 is better than Theorem 5. That is Theorem 5 is better than Theorem 4 sometimes and Theorem 4 is better than Theorem 5 sometimes.

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