

Some results on parallel alternating methods

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Abstract—In this paper, we investigate two parallel alternating methods for solving the system of linear equations $Ax = b$ and give convergence theorems for the parallel alternating methods when the coefficient matrix is a nonsingular H-matrix. Furthermore, we give one example to show our results.

Keywords—nonsingular H-matrix, parallel alternating method, convergence.

I. INTRODUCTION

FOR the large system of linear equations

$$Ax = b, \quad (1)$$

where A is a nonsingular square matrix of order n , $x, b \in R^n$. Benzi and Szyld [1] analyzed the following alternating method:

Given an initial vector $x^{(0)}$, for $k = 0, 1, 2, \dots$,

$$x^{(k+\frac{1}{2})} = M^{-1}Nx^{(k)} + M^{-1}b,$$

$$x^{(k+1)} = P^{-1}Qx^{(k+\frac{1}{2})} + P^{-1}b,$$

where $A = M - N = P - Q$ are two splittings of A . They proved its convergence under certain conditions when the coefficient matrix A is a monotone matrix or a symmetric positive definite matrix.

In paper [2], Climent and Perea introduced two parallel alternating iterative methods.

Assume that

$$A = M_l - N_l = P_l - Q_l, \quad l = 1, 2, \dots, p, \quad (2)$$

where M_l and P_l nonsingular matrices; E_l satisfy $\sum_{l=1}^p E_l = I$ (I is an identity matrix), where E_l are diagonal and $E_l \geq 0$.

Method 1: Let $x^{(0)}$ be a starting vector, $\varepsilon > 0$ is a given precision. For $k = 1, 2, \dots$,

$$x_l^{(k+\frac{1}{2})} = (M_l^{-1}N_l)^{\mu(k,l)}x^{(k)} + \sum_{i=0}^{\mu(k,l)-1} (M_l^{-1}N_l)^i M_l^{-1}b,$$

$$x_l^{(k+1)} = (P_l^{-1}Q_l)^{\nu(k,l)}x_l^{(k+\frac{1}{2})} + \sum_{i=0}^{\nu(k,l)-1} (P_l^{-1}Q_l)^i P_l^{-1}b,$$

$$x^{(k+1)} = \sum_{l=1}^p E_l x_l^{(k+1)},$$

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If $\|x^{(k+1)} - x^{(k)}\| < \varepsilon$, then quit.

It is easy to notice that the iterative matrix of Method 1 is

$$T = \sum_{l=1}^p E_l (P_l^{-1}Q_l)^{\nu(k,l)} (M_l^{-1}N_l)^{\mu(k,l)}.$$

Method 2: Let $x^{(0)}$ be a starting vector, $\varepsilon > 0$ is a given precision. For $k = 1, 2, \dots$,

$$\begin{aligned} x^{(k+\frac{1}{2})} &= \sum_{l=1}^p E_l (M_l^{-1}N_l)^{\mu(k,l)} x^{(k)} \\ &\quad + \sum_{l=1}^p E_l \left[\sum_{i=0}^{\mu(k,l)-1} (M_l^{-1}N_l)^i M_l^{-1} \right] b, \\ x^{(k+1)} &= \sum_{l=1}^p F_l (P_l^{-1}Q_l)^{\nu(k,l)} x_l^{(k+\frac{1}{2})} \\ &\quad + \sum_{l=1}^p F_l \left[\sum_{i=0}^{\nu(k,l)-1} (P_l^{-1}Q_l)^i P_l^{-1} \right] b. \end{aligned}$$

If $\|x^{(k+1)} - x^{(k)}\| < \varepsilon$, then quit.

It is easy to notice that the iterative matrix of Method 2 is

$$S = \left[\sum_{l=1}^p F_l (P_l^{-1}Q_l)^{\nu(k,l)} \right] \left[\sum_{l=1}^p E_l (M_l^{-1}N_l)^{\mu(k,l)} \right].$$

In this paper, we give convergence theorems for the parallel alternating methods when the coefficient matrix is a nonsingular H-matrix.

II. PRELIMINARIES

Let $A \in R^{n \times n}$. We denote by $A \geq 0$ a nonnegative matrix, $|A|$ the absolute value of matrix A , and $\rho(A)$ the spectral radius of A .

Definition 2.1 Let $A = B - C$ be a splitting of A . If $B^{-1} \geq 0, B^{-1}C \geq 0$, then $A = B - C$ is a weak regular splitting[3]. If $B^{-1} \geq 0, C \geq 0$, then $A = B - C$ is a regular splitting[4]. If B is an M-matrix and $C \geq 0$, then $A = B - C$ is an M-splitting[5].

In paper [2], a weak regular splitting is also called a weak nonnegative splitting of the first type.

It's obvious that an M-splitting is a regular splitting and a regular splitting is a weak regular splitting.

Definition 2.2([6]) Let $A \in R^{n \times n}$. $A = M - N$ ($M, N \in R^{n \times n}$) is called as an H-splitting if $\langle M \rangle - |N|$ is an M-matrix. If $\langle A \rangle = \langle M \rangle - |N|$, then $A = M - N$ is called as an H-compatible splitting.

III. CONVERGENCE THEOREMS

In this section, we give convergence theorems for the parallel alternating methods when the coefficient matrix is a nonsingular H-matrix.

Lemma 3.1[2] Let $A \in R^{n \times n}$ and $A^{-1} \geq 0$. If $A = M_l - N_l = P_l - Q_l$ ($l = 1, 2, \dots, p$) are all weak nonnegative splittings of the first type, then

$$\rho(T) < 1,$$

where

$$T = \sum_{l=1}^p E_l(P_l^{-1}Q_l)^{\nu(k,l)}(M_l^{-1}N_l)^{\mu(k,l)}.$$

Lemma 3.2[2] Let $A \in R^{n \times n}$ and $A^{-1} \geq 0$. If $A = M_l - N_l = P_l - Q_l$ ($l = 1, 2, \dots, p$) are all weak nonnegative splittings of the first type, then

$$\rho(S) < 1,$$

where

$$S = \left[\sum_{l=1}^p F_l(P_l^{-1}Q_l)^{\nu(k,l)} \right] \left[\sum_{l=1}^p E_l(M_l^{-1}N_l)^{\mu(k,l)} \right].$$

Lemma 3.3[7] If $A \in R^{n \times n}$ is a nonsingular H-matrix, then $|A^{-1}| \leq A >^{-1}$.

Theorem 3.1 Let $A \in R^{n \times n}$ be a nonsingular H-matrix,

$$A = M_l - N_l = P_l - Q_l \quad (l = 1, 2, \dots, p)$$

are H-splittings while $B \in R^{n \times n}$ be a nonsingular M-matrix,

$$B = \langle M_l \rangle - |N_l| = \langle P_l \rangle - |Q_l| \quad (l = 1, 2, \dots, p),$$

then Method 1 converges to the unique solution of (??) for any starting vector $x^{(0)}$.

Proof: We will show that $\rho(T) < 1$.

It is obvious that $\rho(T) < 1$ if $\rho(|T|) < 1$. From

$$\langle M_l \rangle - |N_l| = \langle P_l \rangle - |Q_l| = B$$

is a nonsingular M-matrix. So $\langle M_l \rangle, \langle P_l \rangle$ ($l = 1, 2, \dots, p$) are all M-matrices, and

$$\langle M_l \rangle - |N_l| = \langle P_l \rangle - |Q_l| = B \quad (l = 1, 2, \dots, p)$$

are M-splittings of B . So M_l, P_l ($l = 1, 2, \dots, p$) are all H-matrices. Moreover,

$$|M_l^{-1}| \leq \langle M_l \rangle^{-1}, |P_l^{-1}| \leq \langle P_l \rangle^{-1}.$$

Thus we obtain

$$\begin{aligned} |T| &= \left| \sum_{l=1}^p E_l(P_l^{-1}Q_l)^{\nu(k,l)}(M_l^{-1}N_l)^{\mu(k,l)} \right| \\ &\leq \sum_{l=1}^p E_l(\langle P_l \rangle^{-1} |Q_l|)^{\nu(k,l)} (\langle M_l \rangle^{-1} |N_l|)^{\mu(k,l)} \\ &= T. \end{aligned}$$

We use Lemma 3.1 to see immediately that $\rho(\bar{T}) < 1$. Therefore, $\rho(|T|) < 1$ and $\rho(T) < 1$, we obtain the conclusion of this theorem.

If $B = \langle A \rangle$ in Theorem 3.1, then we can obtain the following corollary.

Corollary 3.1 Let $A \in R^{n \times n}$ be a nonsingular H-matrix,

$$A = M_l - N_l = P_l - Q_l \quad (l = 1, 2, \dots, p)$$

are H-compatible splittings, then Method 1 converges to the unique solution of (??) for any starting vector $x^{(0)}$.

Theorem 3.2 Let $A \in R^{n \times n}$ be a nonsingular H-matrix,

$$A = M_l - N_l = P_l - Q_l \quad (l = 1, 2, \dots, p)$$

are H-splittings while $B \in R^{n \times n}$ be a nonsingular M-matrix,

$$B = \langle M_l \rangle - |N_l| = \langle P_l \rangle - |Q_l| \quad (l = 1, 2, \dots, p),$$

then Method 2 converges to the unique solution of (??) for any starting vector $x^{(0)}$.

Proof: We will show that $\rho(S) < 1$.

It is obvious that $\rho(S) < 1$ if $\rho(|S|) < 1$. From

$$\langle M_l \rangle - |N_l| = \langle P_l \rangle - |Q_l| = B$$

is a nonsingular M-matrix. So $\langle M_l \rangle, \langle P_l \rangle$ ($l = 1, 2, \dots, p$) are all M-matrices, and

$$\langle M_l \rangle - |N_l| = \langle P_l \rangle - |Q_l| = B \quad (l = 1, 2, \dots, p)$$

are M-splittings of B . So M_l, P_l ($l = 1, 2, \dots, p$) are all H-matrices. Moreover,

$$|M_l^{-1}| \leq \langle M_l \rangle^{-1}, |P_l^{-1}| \leq \langle P_l \rangle^{-1}.$$

Thus we obtain

$$\begin{aligned} |S| &= \left| \left[\sum_{l=1}^p F_l(P_l^{-1}Q_l)^{\nu(k,l)} \right] \left[\sum_{l=1}^p E_l(M_l^{-1}N_l)^{\mu(k,l)} \right] \right| \\ &\leq \sum_{l=1}^p F_l(\langle P_l \rangle^{-1} |Q_l|)^{\nu(k,l)} \sum_{l=1}^p E_l(\langle M_l \rangle^{-1} |N_l|)^{\mu(k,l)} \\ &= S. \end{aligned}$$

We use Lemma 3.2 to see immediately that $\rho(\bar{S}) < 1$. Therefore, $\rho(|S|) < 1$ and $\rho(S) < 1$, we obtain the conclusion of this theorem.

If $B = \langle A \rangle$ in Theorem 3.2, then we can obtain the following corollary.

Corollary 3.2 Let $A \in R^{n \times n}$ be a nonsingular H-matrix,

$$A = M_l - N_l = P_l - Q_l \quad (l = 1, 2, \dots, p)$$

are H-compatible splittings, then Method 2 converges to the unique solution of (??) for any starting vector $x^{(0)}$.

Example

$$A = \begin{bmatrix} 10 & 3 & 8 \\ 4 & 10 & 0 \\ 7 & 3 & 12 \end{bmatrix}$$

is a nonsingular H-matrix. Let

$$M_1 = \begin{bmatrix} 10 & 3 & 5 \\ 5 & 10 & 0 \\ 6 & 5 & 12 \end{bmatrix} \quad M_2 = \begin{bmatrix} 10 & 3 & 6 \\ 5 & 10 & 0 \\ 6 & 5 & 12 \end{bmatrix}$$

$$P_1 = \begin{bmatrix} 10 & 3 & 4 \\ 5 & 10 & 0 \\ 6 & 5 & 12 \end{bmatrix} \quad P_2 = \begin{bmatrix} 10 & 3 & 4 \\ 5 & 10 & 0 \\ 5 & 5 & 12 \end{bmatrix}$$

$$N_l = M_l - A, \quad Q_l = P_l - A \quad (l = 1, 2), \quad \mu(k, l) = \nu(k, l) = 2.$$

It's easy to test that

$$\begin{aligned} <M_1> - |N_1| = <M_2> - |N_2| = <P_1> - |Q_1| \\ = <P_2> - |Q_2| = \begin{bmatrix} 10 & -3 & -8 \\ -6 & 10 & 0 \\ -7 & -7 & 12 \end{bmatrix} \end{aligned}$$

is a nonsingular M-matrix, but

$$\begin{bmatrix} 10 & -3 & -8 \\ -6 & 10 & 0 \\ -7 & -7 & 12 \end{bmatrix} \neq <A>,$$

so

$$A = M_l - N_l = P_l - Q_l \quad (l = 1, 2)$$

are H-splittings.

Case 1: We choose

$$E_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad E_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

then

$$T = \begin{bmatrix} \frac{48}{7033} & -\frac{89}{5135} & -\frac{237}{10805} \\ -\frac{31}{12518} & \frac{123}{21529} & \frac{40}{9861} \\ -\frac{52}{17127} & \frac{212}{15969} & \frac{150}{9149} \end{bmatrix}$$

$$\rho(T) = \frac{103}{3963} < 1.$$

Case 2: We choose $E_1 = I/3$, $E_2 = 2I/3$, $F_1 = 3I/4$, $F_2 = I/4$, $l = 1, 2$, then

$$S = \begin{bmatrix} \frac{191}{31989} & -\frac{119}{7022} & -\frac{231}{12751} \\ -\frac{64}{28429} & \frac{19}{3855} & \frac{25}{6782} \\ -\frac{30}{11587} & \frac{75}{6682} & \frac{133}{8366} \end{bmatrix}$$

$$\rho(S) = \frac{163}{6917} < 1.$$

REFERENCES

- [1] M.Benzi and D.B.Szyld, Existence and uniqueness of splittings for stationary iterative methods with applications to alternating methods, *Numer. Math.*, vol.76, 309-321, 1997.
- [2] J.-J.Climment, C.Perea, L.Tortosa and A.Zamora, Convergence theorems for parallel alternating iterative methods, *Appl. Math. and Comp.*, vol.148, pp.497-517, 2004.
- [3] L.Elsner, Comparisons of weak regular splittings and multisplitting methods, *Numer.Math.*, vol.56, pp.283-289, 1989.
- [4] R.S.Varga, *Matrix Iterative Analysis*, Prentice-Hall, Englewood Cliffs, NJ, 1962.
- [5] H. Schneider, Theorems on M-splittings of a singular M-matrix which depend on graph structure, *Linear Algebra Appl.*, vol.58, pp.407-424, 1984.
- [6] A.Frommer and D.B.Szyld, H-splittings and two-stage iterative methods, *Numer Math.*, vol.63, pp.345-356, 1992.
- [7] A. Ostrowski, Über die determinant mit uberwiegenber hauptdiagonale, *Comment Math. Heh.*, vol.10, pp.69-96, 1937.