

SOLVING NEARLY NON-SIMPLE MATRIX POLYNOMIAL EQUATIONS BY NEWTON'S METHOD WITH ADVANCED LINE SEARCHES

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ABSTRACT.

1. INTRODUCTION

We consider a matrix polynomial equation(MPE) with n -degree defined by

$$(1.1) \quad P(X) = \sum_{k=0}^n A_k X^k = A_n X^n + A_{n-1} X^{n-1} + \cdots + A_1 X + A_0 = 0,$$

where the coefficient matrices A_k 's are $m \times m$ matrices. Then, the unknown matrix X must be an $m \times m$ matrix.

The MPE (1.1) often occurs in the theory of differential equations, system theory, network theory, stochastic theory, quasi-birth-and-death and other areas [1–4, 9, 13, 19–21]. Specially, in quasi-birth-and-death and stochastic problems, finding the minimal nonnegative solution of a matrix equation is an important issue.

There are many researches to find the minimal nonnegative solution. Guo and Laub [12] considered a nonsymmetric algebraic Riccati equation, and they proposed iteration algorithms which converge to the minimal positive solution. In [10], Guo provided a sufficient condition for the existence of nonnegative solutions of nonsymmetric algebraic Riccati equations. Kim [18] showed that the minimal positive solutions also can be found by the Newton method with the zero initial matrices in some different types of quadratic equations. Seo and Kim [25, 28] studied the Newton iteration for matrix polynomial equations.

Newton's method is one of powerful tools to find solutions of nonlinear matrix equations. By Kantorovich theorem [15], the convergence rate of the method is quadratic if the derivative on the domain is Lipschitz continuous and at the solution is nonsingular. But, if the derivative at the solution is singular, then we cannot apply Kantorovich theorem, i.e., we cannot guarantee that the rate is quadratic. The followings are researches to analyze the problems with singular derivative at the solution and improve the method.

For general functions on Banach spaces, Reddien [23], Decker and Kelley [6, 7] gave analyses about Newton's method for singular problems. In [5], Decker, Keller, and Kelley provided an acceleration of Newton's method for singular problems and analyzed for the convergence rate of the method. Kelley and Suresh [17] suggested a new accelerated Newton's method at singular points. Decker and Kelley [8] showed an analysis for Newton's method at nearly singular roots. In [16], Kelley analyzed convergence rate of the method for functions whose high order derivatives at the

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solution are singular. For specific functions on $\mathbb{R}^{m \times n}$, Guo and Lancaster [11] analyzed and provided a modification about Newton's method for algebraic Riccati equations at singular roots. In [26], S.-H. Seo and J.-H. Seo suggested a modified Newton method for matrix polynomial equations with n -degree for singular problems.

In [5, 17], accelerations for Newton's method at singular roots was suggested for general functions on Banach spaces. For specific functions on $\mathbb{R}^{m \times n}$, modifications of Newton's method at singular roots was provided in [11, 27]. But, the main hypotheses of the papers are similar and that the solution is non-simple, i.e., the derivative at the solution is singular. It means that the accelerations for Newton's method cannot be applied and the accelerated iterations cannot be guaranteed converge to the solutions if the solution is simple. Even if the iterations converge to the solutions, they cannot be guaranteed better than the pure iterations.

Otherwise, in [8], authors analyzed and suggested an acceleration for Newton's method about the case of nearly singular roots. In [25], it was suggested that a global accelerated Newton's method, which can be applied whether the solution is simple or not, for (1.1).

The aim of this paper is also to provide an improved Newton's method for (1.1) which satisfies following Assumption 1.1 at nearly singular roots. We show that the differences between the Newton sequences and the solution lie on nearly one-dimensional space. Moreover, with the exact line search idea in [24], we suggest a proper acceleration weight α .

Assumption 1.1. For the MPE (1.1),

- 1) The coefficient matrices A_k 's are nonnegative except A_1 .
- 2) $-A_1$ is a nonsingular M -matrix.
- 3) A_0 , A_1 , and $\sum_{k=2}^n A_k$ are irreducible.

Here, we give some basic definitions and lemmas for this paper.

Let $A, B \in \mathbb{R}^{m \times m}$ be matrices. If all elements of A is nonnegative, then we call that A is a *nonnegative* matrix and denote $A \geq 0$. In similar sense, we define $A \leq 0$, $A > 0$, and $A < 0$. If a matrix A can be written as $rI - B$ with $B \geq 0$ and $r \in \mathbb{R}$, we call that A is a *Z-matrix*. Moreover, if $A = rI - B$ is a *Z-matrix* and $r \geq \rho(B)$ then A is called an *M-matrix*. The following is a basic theorem for *M-matrices*.

Theorem 1.2. For a *Z-matrix* A , the following are equivalent:

- (1) A is a nonsingular *M-matrix*.
- (2) A^{-1} is nonnegative.
- (3) $Av > 0$ for some vector $v > 0$.
- (4) All eigenvalues of A have positive real parts.

Let a function $F : \mathbb{R}^{m \times n} \rightarrow \mathbb{R}^{m \times n}$ and an equation $F(X) = 0$ be given. If nonnegative solutions S_1 and S_2 of $F(X) = 0$ are satisfy

$$(1.2) \quad S_1 \leq S \leq S_2,$$

for any nonnegative solution S of $F(X) = 0$, then they are called the *minimal nonnegative solution* and the *maximal nonnegative solution*, respectively. The *minimal positive solution* and the *maximal positive solution* also are can be defined, similarly. If the Fréchet derivative of F at a solution S is nonsingular, then S is called *simple*. Furthermore, we call that a not simple solution is *non-simple*. In this paper, for convenience, the notation $\|\cdot\|$ is used instead of the Frobenius norm $\|\cdot\|_F$ and \mathbb{N}_0 is defined by $\mathbb{N} \cup \{0\}$ because they are used very frequently.

2. CONVERGENCE OF NEWTON'S METHOD FOR THE MPE

In this paper, we denote that

$$(2.1) \quad P'_X(H) = \sum_{k=1}^n \sum_{l=0}^{k-1} A_k X^l H X^{k-l-1}$$

is the Fréchet derivative of the MPE (1.1) at X in the direction H , and the second Fréchet derivative at X is given by

$$(2.2) \quad P''_X(K, H) = \sum_{k=2}^n \sum_{l=0}^{k-2} \sum_{j=0}^l A_k (X^l H X^j K X^{n-l-j-2} + X^l K X^j H X^{n-l-j-2}).$$

For given initial guess X_0 , the Newton iteration of (1.1)

$$(2.3) \quad X_{i+1} = X_i - P'^{-1}_{X_i}(P(X_i))$$

can be separated into two parts as

$$(2.4) \quad \begin{cases} P'_{X_i}(H_i) = -P(X_i), \\ X_{i+1} = X_i + H_i, \end{cases} \quad i = 1, 2, \dots$$

If we define that

$$(2.5) \quad \mathcal{P}'_X = \text{vec} \circ P'_X \circ \text{vec}^{-1} = \sum_{k=1}^n \sum_{l=0}^{k-1} (X^{k-l-1})^T \otimes A_k X^l,$$

then solving (2.4) is equivalent to solving the following $m^2 \times m^2$ linear system

$$(2.6) \quad \mathcal{P}'_{X_i} \text{vec}(H_i) = \text{vec}(-P(X_i)),$$

where vec is the vectorization.

We introduce a sufficient condition of the existence of the minimal nonnegative solution of the MPE (1.1) with Assumption 1.1, and give some analysis for Newton's method.

Theorem 2.1. [22, Theorem 2.1] *Let the MPE (1.1) with 1) and 2) in Assumption 1.1 be given. Then, there exists the minimal nonnegative solution if*

$$(2.7) \quad B = -\sum_{k=0}^n A_k \text{ is a nonsingular or singular irreducible } M\text{-matrix.}$$

Theorem 2.2. [27, Theorem 2.2] *Suppose that the MPE (1.1) satisfies Assumption 1.1 and (2.7). Then, the Newton sequence $\{X_i\}$ with $X_0 = 0$ is well defined, is monotone nondecreasing, and converges to the elementwise minimal positive solution S . Furthermore, $-\mathcal{P}'_{X_i}$ is a nonsingular irreducible M -matrix for $i \in \mathbb{N}$, and $-\mathcal{P}'_S$ is an irreducible M -matrix.*

The next theorem follows directly from Theorem 2.2 and the well known local quadratic convergence of Newton's method.

Theorem 2.3. *If the matrix $-\mathcal{P}'_S$ in Theorem 2.2 is nonsingular, then for $X_0 = 0$, the Newton sequence $\{X_i\}$ converges to S , quadratically.*

3. ANALYSIS FOR THE SINGULAR M -MATRIX $-\mathcal{P}'_S$

According to Theorem 2.3, the Newton iteration (2.3) converges quadratically if $-\mathcal{P}'_S$ is nonsingular. In this section, we will see the convergence rate of (2.3) when $-\mathcal{P}'_S$ is a singular M -matrix. If P'_S is not invertible, then P'_S has a null space $\mathcal{N} = \text{Ker}(P'_S)$ and closed range $\mathcal{M} = \text{Im}(P'_S)$. Suppose that the direct sum $\mathcal{N} \oplus \mathcal{M} = \mathbb{R}^{m \times m}$. Then, we can define $\mathbf{P}_{\mathcal{N}}$ to be the projection onto \mathcal{N} parallel to

\mathcal{M} and $\mathbf{P}_{\mathcal{M}} = I - \mathbf{P}_{\mathcal{N}}$. For a nonzero matrix $N_0 \in \mathcal{N}$, define the map $\mathcal{B}_{N_0} : \mathcal{N} \rightarrow \mathcal{N}$ given by

$$(3.1) \quad \mathcal{B}_{N_0}(N) = \mathbf{P}_{\mathcal{N}} P_S''(N_0, N).$$

In fact, \mathcal{B}_{N_0} is a linear map. The main result of this section is an application of the following theorem which shows the local convergence and the convergence rate of Newton's method under some conditions.

Theorem 3.1. (cf. [11, Theorem 1.5], [16, Theorem 1.1]) *Let \mathcal{B}_{N_0} in (3.1) be invertible for some nonzero $N_0 \in \mathcal{N}$, $\mathcal{N} = \text{span}\{N_0\} \oplus \mathcal{N}_1$ for some subspace \mathcal{N}_1 , and let*

$$(3.2) \quad W(\rho, \theta, \eta) = \left\{ X \mid \begin{array}{l} 0 < \|X - S\| < \rho, \|\mathbf{P}_{\mathcal{M}}(X - S)\| \leq \theta \|\mathbf{P}_{\mathcal{N}}(X - S)\|, \\ \|(\mathbf{P}_{\mathcal{N}} - \mathbf{P}_0)(X - S)\| \leq \eta \|\mathbf{P}_{\mathcal{N}}(X - S)\| \end{array} \right\},$$

where \mathbf{P}_0 is the projection onto $\text{span}\{N_0\}$ parallel to $\mathcal{N}_1 \oplus \mathcal{M}$. If $X_0 \in W(\rho_0, \theta_0, \eta_0)$ for ρ_0, θ_0, η_0 sufficiently small, then the Newton sequence $\{X_i\}$ is well defined and $\|P_{X_i}'^{-1}\| \leq c \|X_i - S\|^{-1}$ for all $i \geq 1$ and some constant $c > 0$. Moreover,

$$\lim_{i \rightarrow \infty} \frac{\|X_{i+1} - S\|}{\|X_i - S\|} = \frac{1}{2}, \quad \lim_{i \rightarrow \infty} \frac{\|\mathbf{P}_{\mathcal{M}}(X_i - S)\|}{\|\mathbf{P}_{\mathcal{N}}(X_i - S)\|^2} = 0.$$

To analyze convergence of Newton's method when $-\mathcal{P}'_S$ is singular, we will show that (1.1) satisfies the conditions of Theorem 3.1. From this point, for convenience, we let $\tilde{X}_i = X_i - S$.

Lemma 3.2. *Suppose the matrix polynomial equation (1.1) satisfies Assumption 1.1. If the matrix $-\mathcal{P}'_S$ is a singular M -matrix, then 0 is a simple eigenvalue of $-\mathcal{P}'_S$, $\mathcal{N} \oplus \mathcal{M} = \mathbb{R}^{m \times m}$, \mathcal{N} is one-dimensional and the map \mathcal{B}_{N_0} is invertible for some nonzero $N_0 \in \mathcal{N}$.*

Proof. Since S is positive and A_k 's are irreducible, $-\mathcal{P}'_S$ is irreducible. Then, by Perron-Frobenius Theorem [14, Theorem 8.4.4], 0 is a simple eigenvalue of \mathcal{P}'_S with a positive eigenvector. Thus, we can find n^2 linearly independent vectors $\chi_1, \chi_2, \dots, \chi_{n^2}$ such that $\chi_1 > 0$ and

$$(3.3) \quad \mathcal{X}^{-1} \mathcal{P}'_S \mathcal{X} = \begin{bmatrix} 0 & 0 \\ 0 & \mathcal{D} \end{bmatrix}, \text{ where } \mathcal{X} = \left[\begin{array}{c|c|c|c} \chi_1 & \chi_2 & \cdots & \chi_{n^2} \end{array} \right]$$

and \mathcal{D} is an $(n^2 - 1) \times (n^2 - 1)$ nonsingular matrix. By the same way, we also have a positive vector ψ such that $\psi^T \mathcal{P}'_S = 0$. Now, $P'_S(N) = 0$ if and only if $\mathcal{P}'_S \text{vec}(N) = 0$. From (3.3), $\mathcal{P}'_S \text{vec}(N) = 0$ if and only if $\text{vec}(N) \in \text{span}(\chi_1)$, in which case we write $N = a \text{vec}^{-1}(\chi_1)$ for some nonzero $a \in \mathbb{R}$. Thus, $\mathcal{N} = \text{span}(\text{vec}^{-1}(\chi_1))$. Similarly, $\mathcal{M} = \text{span}(\text{vec}^{-1}(\chi_2), \dots, \text{vec}^{-1}(\chi_{n^2}))$. Therefore, \mathcal{N} is one-dimensional and $\mathbb{R}^{m \times m} = \mathcal{N} \oplus \mathcal{M}$.

To prove the map \mathcal{B}_{N_0} is invertible for a nonzero matrix $N_0 \in \mathcal{N}$, we only need to show that

$$\mathbf{P}_{\mathcal{N}}(P_S''(N_0, N)) \neq 0,$$

for all nonzero $N \in \mathcal{N}$ because \mathcal{B}_{N_0} is linear and \mathcal{N} is one-dimensional. Since $\text{vec}^{-1}(\chi_1) > 0$ and $S > 0$, we have

$$\begin{aligned} P_S''(N_0, N) &= \sum_{k=2}^n \sum_{l=0}^{k-2} \sum_{j=0}^l A_k (S^l N_0 S^j N S^{n-l-j-2} + S^l N S^j N_0 S^{n-l-j-2}) \\ &= 2ab \sum_{k=2}^n \sum_{l=0}^{k-2} \sum_{j=0}^l A_k (S^l \text{vec}^{-1}(\chi_1) S^j \text{vec}^{-1}(\chi_1) S^{n-l-j-2}) \neq 0 \end{aligned}$$

where $N = a\text{vec}^{-1}(\chi_1)$ and $N_0 = b\text{vec}^{-1}(\chi_1)$. Moreover, $P_S''(N_0, N)$ is either positive or negative.

On the other hand,

$$\text{vec}(P_S''(N_0, N)) = k_1\chi_1 + k_2\chi_2 + \cdots + k_{n^2}\chi_{n^2}$$

for some real numbers k_1, k_2, \dots, k_{n^2} . By Fundamental theorem of linear algebra in [29] and Lemma 6.3.10 in [14], we have

$$(3.4) \quad \psi^T \text{vec}(P_S''(N_0, N)) = k_1 \psi^T \chi_1.$$

Since $P_S''(N_0, N)$ is either positive or negative and ψ is positive, the left side of (3.4) is also either positive or negative. So, k_1 cannot be zero. Therefore,

$$\mathbf{P}_{\mathcal{N}}(P_S''(N_0, N)) = k_1 \text{vec}^{-1}(\chi_1) \neq 0.$$

□

Lemma 3.3. *Let S be the minimal positive solution of (1.1) with Assumption 1.1, and let $\{X_i\}_{i=0}^\infty$ be a Newton sequence in (2.3). Then,*

$$\|P(X_i)\| \leq a\|\tilde{X}_i\|^2 + b\|\tilde{X}_i\|\|\tilde{X}_{i-1}\| + c\|\tilde{X}_{i-1}\|^2$$

for some positive real numbers a, b, c .

Proof. From Taylor's Theorem and putting $S = X_{i-1} - \tilde{X}_{i-1}$, we have

$$(3.5) \quad P(X_i) = P(S) + P'_S(X_i - S) + O(\|X_i - S\|^2),$$

and

$$0 = P(S) = P(X_{i-1} - \tilde{X}_{i-1}) = P(X_{i-1}) - P'_{X_{i-1}}(\tilde{X}_{i-1}) + O(\|\tilde{X}_{i-1}\|^2),$$

which is equivalent to

$$(3.6) \quad -P(X_{i-1}) + P'_{X_{i-1}}(\tilde{X}_{i-1}) = O(\|\tilde{X}_{i-1}\|^2).$$

From (2.4), we have

$$(3.7) \quad 0 = P'_{X_{i-1}}(X_i - X_{i-1}) + P(X_{i-1}),$$

and clearly

$$(3.8) \quad X_i - X_{i-1} = \tilde{X}_i - \tilde{X}_{i-1}.$$

If we subtract (3.7) from (3.5) and substitute (3.6), we obtain

$$\begin{aligned} P(X_i) &= P(S) + P'_S(\tilde{X}_i) - P(X_{i-1}) - P'_{X_{i-1}}(\tilde{X}_i - \tilde{X}_{i-1}) + O(\|\tilde{X}_i\|^2) \\ &= P'_S(\tilde{X}_i) - P'_{X_{i-1}}(\tilde{X}_i) + O(\|\tilde{X}_i\|^2) + O(\|\tilde{X}_{i-1}\|^2). \end{aligned}$$

Putting $S = X_{i-1} - \tilde{X}_{i-1}$ in the previous equality,

$$\begin{aligned} P(X_i) &= \sum_{k=1}^n \sum_{l=0}^{k-1} A_k (X_{i-1} - \tilde{X}_{i-1})^l \tilde{X}_i (X_{i-1} - \tilde{X}_{i-1})^{k-l-1} \\ &\quad - P'_{X_{i-1}}(\tilde{X}_i) + O(\|\tilde{X}_i\|^2) + O(\|\tilde{X}_{i-1}\|^2) \\ &= \sum_{k=1}^n \sum_{l=0}^{k-1} A_k X_{i-1}^l \tilde{X}_i X_{i-1}^{k-l-1} + O(\|\tilde{X}_i\|\|\tilde{X}_{i-1}\|) \\ &\quad - P'_{X_{i-1}}(\tilde{X}_i) + O(\|\tilde{X}_i\|^2) + O(\|\tilde{X}_{i-1}\|^2) \\ &= P'_{X_{i-1}}(\tilde{X}_i) + O(\|\tilde{X}_i\|\|\tilde{X}_{i-1}\|) - P'_{X_{i-1}}(\tilde{X}_i) + O(\|\tilde{X}_i\|^2) + O(\|\tilde{X}_{i-1}\|^2) \\ &= O(\|\tilde{X}_{i-1}\|^2) + O(\|\tilde{X}_i\|\|\tilde{X}_{i-1}\|) + O(\|\tilde{X}_i\|^2). \end{aligned}$$

Since $\|\cdot\|$ is a multiplicative matrix norm on $\mathbb{R}^{m \times m}$, we have required result. □

Lemma 3.4. *For any fixed $\theta > 0$, let*

$$\mathcal{Q} = \{i \in \mathbb{N} \cup \{0\} \mid \|\mathbf{P}_{\mathcal{M}}(\tilde{X}_i)\| > \theta \|\mathbf{P}_{\mathcal{N}}(\tilde{X}_i)\|\}$$

where $\{X_i\}$ is the Newton sequence in Theorem 2.2. Then, there exist an integer i_0 and a constant $c > 0$ such that $\|\tilde{X}_i\| \leq c\|\tilde{X}_{i-1}\|^2$ for all $i \geq i_0$ in \mathcal{Q} .

Proof. Using Taylor's Theorem and the fact that $P'_S(\mathbf{P}_{\mathcal{N}}(\tilde{X}_i)) = 0$,

$$(3.9) \quad P(X_i) = P(S) + P'_S(\tilde{X}_i) + O(\|\tilde{X}_i\|^2) = P'_S(\mathbf{P}_{\mathcal{M}}(\tilde{X}_i)) + O(\|\tilde{X}_i\|^2).$$

Since $P'_S|_{\mathcal{M}} : \mathcal{M} \rightarrow \mathcal{M}$ is invertible, $\|P'_S(\mathbf{P}_{\mathcal{M}}(\tilde{X}_i))\| \geq c_1 \|\mathbf{P}_{\mathcal{M}}(\tilde{X}_i)\|$ for some constant $c_1 > 0$. For $i \in \mathcal{Q}$, we have

$$\|\tilde{X}_i\| \leq \|\mathbf{P}_{\mathcal{M}}(\tilde{X}_i)\| + \|\mathbf{P}_{\mathcal{N}}(\tilde{X}_i)\| \leq (\theta^{-1} + 1) \|\mathbf{P}_{\mathcal{M}}(\tilde{X}_i)\|.$$

Thus by (3.9),

$$(3.10) \quad \|P(X_i)\| \geq c_1 \|\mathbf{P}_{\mathcal{M}}(\tilde{X}_i)\| - c_2 \|\tilde{X}_i\|^2 \geq c_1(\theta^{-1} + 1)^{-1} \|\tilde{X}_i\| - c_2 \|\tilde{X}_i\|^2.$$

On the other hand, from Lemma 3.3, we have

$$\|P(X_i)\| \leq c_3 \|\tilde{X}_i\|^2 + c_4 \|\tilde{X}_{i-1}\| \|\tilde{X}_i\| + c_5 \|\tilde{X}_{i-1}\|^2.$$

From (3.10) and the fact that $X_i \neq S$ for any i , we have

$$c_1(\theta^{-1} + 1)^{-1} - c_2 \|\tilde{X}_i\| \leq c_3 \|\tilde{X}_i\| + c_4 \|\tilde{X}_{i-1}\| + c_5 \frac{\|\tilde{X}_{i-1}\|^2}{\|\tilde{X}_i\|}.$$

Since \tilde{X}_i converges to 0 by Theorem 2.2, we can find an i_0 such that $\|\tilde{X}_i\| \leq c\|\tilde{X}_{i-1}\|^2$ for all $i \geq i_0$. \square

Corollary 3.5. *Assume that, for given $\theta > 0$, $\|\mathbf{P}_{\mathcal{M}}(\tilde{X}_i)\| > \theta \|\mathbf{P}_{\mathcal{N}}(\tilde{X}_i)\|$ for all i large enough. Then $X_i \rightarrow S$ quadratically.*

When P'_S is singular practically the Newton sequence converges linearly, according to the corollary we conclude that *the error will generally be dominated by its \mathcal{N} component* [11]. From Lemmas 3.2 and 3.4 we have the following main theorem.

Theorem 3.6. *If $-P'_S$ is a singular M -matrix and the convergence rate of the Newton sequence $\{X_i\}$ in Theorem 2.2 is not quadratic, then $\|P'_{X_i}\| \leq c\|\tilde{X}_i\|^{-1}$ for all $i \geq 1$ and some constant $c > 0$. Moreover,*

$$\lim_{i \rightarrow \infty} \frac{\|\tilde{X}_{i+1}\|}{\|\tilde{X}_i\|} = \frac{1}{2}, \quad \lim_{i \rightarrow \infty} \frac{\|\mathbf{P}_{\mathcal{M}}(\tilde{X}_i)\|}{\|\mathbf{P}_{\mathcal{N}}(\tilde{X}_i)\|^2} = 0.$$

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