Modified CGLS Iterative Algorithm for Solving the Generalized Sylvester-Conjugate Matrix Equation

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Abstract. By introducing the real inner product, this paper offers an modified conjugate gradient least squares iterative algorithm (MCGLS) for solving the generalized Sylvester-conjugate matrix equation. The properties of this algorithm are discussed and the finite convergence of this algorithm is proven. This new iterative method can obtain the symmetric least squares Frobenius norm solution within finite iteration steps in the absence of roundoff errors. Finally, two numerical examples are offered to illustrate the effectiveness of the proposed algorithm.

1. Introduction

Matrix equations often arise from system theory, control theory, neural network, and stability analysis [1-6]. How to solve these matrix equations become an important topic which have received much attention [7-15]. Some different methods have been implemented for solving various linear matrix equations.

Recently, by applying the hierarchical identification principle, Ding et al introduced gradient based iterative algorithms to solve (coupled) generalized Sylvester matrix equations, nonlinear systems [16-25]. For more references, one can refer to [26-32]. Furthermore, the least squares solution to the matrix equations have been focused by many researchers [33-40]. For instance, the LSQR iterative algorithms are used to solve the reflexive least squares solutions of the generalized Sylvester matrix equation $A_1X_1B_1 + A_2X_2B_2 + \cdots + A_lX_lB_l = C$ [34], reflexive least squares solutions of the general coupled matrix equations [37], (R,S)-symmetric least squares solutions of the general coupled matrix equations [38], symmetric least squares solutions of the matrix equation $AXB + CYD = E$ [39]. Very recently, Hajarian [33, 35] extends the conjugate gradient least squares iterative algorithm to solve the general coupled matrix equations and the generalized Sylvester-transpose matrix equations.

Motivated by the above work, in this paper we denote a real inner product over complex field and propose an modified CGLS iterative algorithm (MCGLS) for solving the generalized Sylvester-conjugate matrix equation.
This paper focuses on the following two problems.

**Problem 1.** For given \( A_1 \in \mathbb{C}^{m \times n}, B_i \in \mathbb{C}^{n \times q}, C_j \in \mathbb{C}^{p \times q}, D_j \in \mathbb{C}^{p \times q}, E \in \mathbb{C}^{m \times q}, i = 1, 2, \ldots, p \) and \( j = 1, 2, \ldots, t \), find symmetric matrix \( X^* \in \mathbb{C}^{m \times n} \) such that

\[
\sum_{i=1}^{p} A_i X B_i + \sum_{j=1}^{t} C_j \bar{X} D_j = E,
\]

(1.1)

\[
\| \sum_{i=1}^{p} A_i X B_i + \sum_{j=1}^{t} C_j \bar{X} D_j - E \| = \min_{X \in \mathbb{C}^{m \times n}} \| \sum_{i=1}^{p} A_i X B_i + \sum_{j=1}^{t} C_j \bar{X} D_j - E \|.
\]

(1.2)

**Problem 2.** Let \( S_p \) denote the solution set of Problem 1, for given symmetric matrix \( X_0 \in \mathbb{C}^{m \times n} \), find the matrix \( \hat{X} \in S_p \), such that

\[
\| \hat{X} - X_0 \| = \min_{X \in S_p} \| X - X_0 \|.
\]

(1.3)

The remainder of the paper is organized as follows. Section 2 offers the symbols and the preliminaries. Section 3 brings the modified CGLS iterative algorithm. It is shown that the proposed algorithm can obtain the solution of Problem 1 for any initial matrix within a finite number of iterations in the absence of roundoff errors. Two numerical examples are offered in Section 4 to illustrate the effectiveness of the proposed algorithm. Finally, some concluding remarks are given in Section 5.

2. The symbols and preliminaries

Before starting this section, we first introduce the following notations which will be used in the rest of this paper. \( \mathbb{C}^{m \times n} \) denotes the set of \( m \times n \) complex matrices. For a matrix \( A \in \mathbb{C}^{m \times n} \), we denote its transpose, conjugate, conjugate transpose, trace, Frobenius norm and column space by \( A^T, \bar{A}, A^H, \text{tr}(A), \|A\| \) and \( R(A) \), respectively. Let \( I_n \) and \( S_n \) denote the \( n \times n \) unit matrix and reverse unit matrix respectively. The symbol \( \text{vec}(\cdot) \) stands for the vec operator, i.e., for \( A = (a_1, a_2, \ldots, a_n) \in \mathbb{C}^{m \times n} \), where \( a_i(i = 1, 2, \ldots, n) \) denotes the \( i \)th column of \( A \), \( \text{vec}(A) = (a_1^T, a_2^T, \ldots, a_n^T)^T \).

For \( X \) and \( Y \) two matrices in \( \mathbb{C}^{m \times n} \), we define real inner product as

\[
\langle X, Y \rangle = \text{Re} [\text{tr}(Y^H X)].
\]

According this definition, the real inner product has the following properties.

(1) \( \langle X, Y \rangle = \langle Y, X \rangle \),
(2) \( \langle kX, Y \rangle = k \langle X, Y \rangle, k \in \mathbb{R} \),
(3) \( \langle X + Y, Z \rangle = \langle X, Z \rangle + \langle Y, Z \rangle \),
(4) \( \langle X, X \rangle > 0 \), for all \( X \neq 0 \),
(5) For matrices \( K, A, B \) and \( X \) with appropriate dimension, \( \langle R, A X B \rangle = \langle A^H R B^H, X \rangle \),
(6) For matrices \( R, A, B \) and \( X \) with appropriate dimension, \( \langle R, A \bar{X} B \rangle = \langle A^H R B^H, X \rangle \),
(7) Two matrices \( X \) and \( Y \) are said to be orthogonal if \( \langle X, Y \rangle = 0 \).

The induced-norm of a matrix \( A \) is defined by the following formula:

\[
\|A\| = \sqrt{\langle A, A \rangle} = \sqrt{\text{Re} [\text{tr}(A^H A)]} = \sqrt{\text{tr}[A^H A]}.
\]

The associated norm is the well-known Frobenius norm.

**Lemma 1** ([41]) Let \( U \) be an inner product space, \( V \) be a subspace of \( U \), and \( V^\perp \) be the orthogonal complement subspace of \( V \). For a given \( u \in U \), if there exists a \( v_0 \in V \) such that \( \|u - v_0\| \leq \|u - v\| \) holds for any \( v \in V \), then \( v_0 \) is unique and \( v_0 \in V \) is the unique minimization vector in \( V \) if and only if \( (u - v_0) \bot V \), i.e. \( (u - v_0) \in V^\perp \).
Lemma 2 Suppose that $\hat{R}$ is the residual of Eq.(1.1) corresponding to the symmetric matrix $\hat{X} \in \mathbb{C}^{m \times n}$, that is, $\hat{R} = E - \sum_{i=1}^{p} \frac{1}{2}(A_i \hat{X} B_i + A_i \hat{X}^T B_i) - \sum_{i=1}^{t} \frac{1}{2}(C_i \hat{X} D_i + C_i \hat{X}^H D_i)$. If

$$
\sum_{i=1}^{p} \frac{1}{2}(A_i^H R B_i^H + B_i^T R A_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j^H R D_j^H + D_j R^H C_j) = 0.
$$

holds, then the symmetric matrix $\hat{X}$ is the symmetric least squares solution of Eq.(1.1).

Proof. Firstly, we define the linear subspace $W = \{F \mid F = \sum_{i=1}^{p} \frac{1}{2}(A_i X B_i + A_i X^T B_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j X D_j + C_j X^H D_j) \}$ with $A_i \in \mathbb{C}^{m \times q}, B_i \in \mathbb{C}^{q \times n}, C_j \in \mathbb{C}^{m \times q}, D_j \in \mathbb{C}^{n \times q}, E \in \mathbb{C}^{p \times q}$, and $X \in \mathbb{C}^{m \times n}$. Hence, for any $F \in W$, one can obtain

$$
\langle E - F, F \rangle = \langle E - \sum_{i=1}^{p} \frac{1}{2}(A_i X B_i + A_i X^T B_i) - \sum_{j=1}^{t} \frac{1}{2}(C_j X D_j + C_j X^H D_j), F \rangle = \langle \hat{R}, \sum_{i=1}^{p} \frac{1}{2}(A_i X B_i + A_i X^T B_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j X D_j + C_j X^H D_j) \rangle = \langle \hat{R}, \sum_{i=1}^{p} \frac{1}{2}(A_i^H R B_i^H + B_i^T R A_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j^H R D_j^H + D_j R^H C_j), X \rangle
$$

Therefore, if we let $\sum_{i=1}^{p} \frac{1}{2}(A_i^H R B_i^H + B_i^T R A_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j^H R D_j^H + D_j R^H C_j) = 0$, it is can be proved that the above equation $(E - \hat{F}, F) = 0$. It follows from Lemma 1 that $(E - \hat{F}) \in W$. Therefore, the matrix $\hat{X}$ is the symmetric least squares solution of Eq.(1.1). □

Lemma 3 Let $\hat{X}$ be a symmetric solution of Problem 1, then any symmetric solution $\hat{X}$ of Problem 1 can be expressed as $\hat{X} = Z$, where the matrix $Z \in \mathbb{C}^{m \times n}$ satisfies

$$
\sum_{i=1}^{p} \frac{1}{2}(A_i Z B_i + A_i Z^T B_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j Z D_j + C_j Z^H D_j) = 0.
$$

(2.1)

Proof. Let $\hat{X}$ be any solution of Problem 1, if we define the matrix $Z = \hat{X} - \hat{X}$, then we have $\hat{X} = \hat{X} + Z$. Now it is showed that Eq.(2.1) holds. By applying Lemma 2, we can obtain

$$
\| \sum_{i=1}^{p} \frac{1}{2}(A_i \hat{X} B_i + A_i \hat{X}^T B_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j \hat{X} D_j + C_j \hat{X}^H D_j) - E \|^2 = \| \sum_{i=1}^{p} \frac{1}{2}(A_i \hat{X} B_i + A_i \hat{X}^T B_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j \hat{X} D_j + C_j \hat{X}^H D_j) - E \|^2
$$
Step 4. Compute
\[ \| \sum_{i=1}^{p} \frac{1}{2} [A_i(\hat{X} + Z)B_i + A_i(\hat{X} + Z)^T B_i - D_j] + \sum_{j=1}^{t} \frac{1}{2} [C_j(\hat{X} + Z)D_j + C_j(\hat{X} + Z)^T D_j - E] \|^2 \]

\[ = \| \sum_{i=1}^{p} \frac{1}{2} (A_i Z B_i + A_i Z^T B_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j Z D_j + C_j Z^T D_j) - \hat{R} \|^2 \]

\[ = \| \sum_{i=1}^{p} \frac{1}{2} (A_i Z B_i + A_i Z^T B_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j Z D_j + C_j Z^T D_j) \|^2 + \| \hat{R} \|^2 \]

\[ - 2 \sum_{i=1}^{p} \frac{1}{2} (A_i R B_i^T + B_i R^T A_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j R D_j^T + D_j R^T C_j) \]

\[ = \| \sum_{i=1}^{p} \frac{1}{2} (A_i Z B_i + A_i Z^T B_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j Z D_j + C_j Z^T D_j) \|^2 + \| \hat{R} \|^2 \]

This shows that the Eq.(2.1) holds. □

3. Main results

In this section, the modified CGLS iterative algorithm (MCGLS) for solving the symmetric least squares problem of Eq. (1.1) will be offered and some properties of this algorithm will be established.

Algorithm 1. Step 1. Input matrices \( A_i \in C^{m \times n}, B_i \in C^{n \times d}, C_j \in C^{p \times n}, D_j \in C^{p \times p}, E \in C^{m \times q} \) and \( X(1) \in C^{m \times q} \) for \( i = 1, 2, \cdots, p, j = 1, 2, \cdots, t \);

Step 2. Compute
\[ R(1) = E - \sum_{i=1}^{p} \frac{1}{2} (A_i X(1) B_i + A_i X(1)^T B_i) - \sum_{j=1}^{t} \frac{1}{2} (C_j X(1) D_j + C_j X(1)^T D_j); \]

\[ S(1) = \sum_{i=1}^{p} \frac{1}{2} \left( A_i^T R(1) B_i^T + B_i R(1)^T A_i \right) + \sum_{j=1}^{t} \frac{1}{2} \left( C_j^T R(1) D_j^T + D_j R(1)^T C_j \right); \]

\[ P(1) = S(1), \quad \gamma(1) = \|S(1)\|^2; \]

For \( k = 1, 2, 3, \cdots \) repeat the following:

Step 3. If \( \| R(k) \| = 0 \), then stop and \( X(k) \) is the solution of Eq.(1.6), break;

else if \( \| R(k) \| \neq 0 \) but \( \| S(k) \| = 0 \), then stop and \( X(k) \) is the solution of Problem 1, break;

else \( k := k + 1 \);

Step 4. Compute
\[ Q(k) = \sum_{i=1}^{p} \frac{1}{2} (A_i P(k) B_i + A_i P(k)^T B_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j P(k) D_j + C_j P(k)^T D_j); \]

\[ \delta(k) = \gamma(k)/\|Q(k)\|^2; \]

\[ X(k+1) = X(k) + \delta(k) P(k); \]

\[ R(k+1) = R(k) - \delta(k) Q(k); \]

\[ S(k+1) = \sum_{i=1}^{p} \frac{1}{2} \left( A_i^T R(k+1) B_i^T + B_i R(k+1)^T A_i \right) + \sum_{j=1}^{t} \frac{1}{2} \left( C_j^T R(k+1) D_j^T + D_j R(k+1)^T C_j \right); \]

\[ = S(k) - \delta(k) \left( \sum_{i=1}^{p} \frac{1}{2} \left( A_i^T Q(k) B_i^T + B_i Q(k)^T A_i \right) + \sum_{j=1}^{t} \frac{1}{2} \left( C_j^T Q(k) D_j^T + D_j Q(k)^T C_j \right) \right); \]

\[ \gamma(k+1) = \|S(k+1)\|^2; \]

\[ \lambda(k) = \gamma(k+1)/\gamma(k); \]

\[ P(k+1) = S(k+1) + \lambda(k) P(k). \]
Step 5. Go to Step 3.

Some basic properties of Algorithm 1 are listed in the following lemmas.

**Lemma 4.** For the sequences $S(k), P(k)$ and $Q(k)$ which are generated by Algorithm 1, if there exists a positive number $r$, such that $\|S(u)\| \neq 0$ and $\|Q(u)\| \neq 0$, $\forall u = 1, 2, \ldots, r$, then the following statements hold for $u, v = 1, 2, \ldots, r$ and $u \neq v$.

1. $\langle S(u), S(v) \rangle = 0$,
2. $\langle Q(u), Q(v) \rangle = 0$,
3. $\langle P(u), S(v) \rangle = 0$.

**Proof.** Step 1: We prove the conclusion by induction. Because the real inner product is commutative, it is enough to prove three statements for $1 \leq u < v \leq r$.

For $u = 1, v = 2$, by Algorithm 1, one can obtain

\[
\langle S(1), S(2) \rangle = \langle S(1), S(1) - \delta(1) \sum_{i=1}^{p} \frac{1}{2} (A_i^H Q(1) B_i^T + \overline{B}_i Q(1) A_i^T) + \sum_{j=1}^{t} \frac{1}{2} (C_j^H Q(1) D_i^T + D_i^T Q(1) C_j) \rangle = \|S(1)\|^2 - \delta(1) \langle S(1), \sum_{i=1}^{p} \frac{1}{2} (A_i^H Q(1) B_i^T + \overline{B}_i Q(1) A_i^T) + \sum_{j=1}^{t} \frac{1}{2} (C_j^H Q(1) D_i^T + D_i^T Q(1) C_j) \rangle = \|S(1)\|^2 - \delta(1) \langle S(1), \sum_{i=1}^{p} \frac{1}{2} (A_i S(1) B_i + A_i S(1)^T B_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j S(1) D_i + C_j S(1)^T D_i), Q(1) \rangle = \|S(1)\|^2 - \delta(1) \langle Q(1), Q(1) \rangle = 0,
\]

\[
\langle Q(1), Q(2) \rangle = \langle Q(1), \sum_{i=1}^{p} \frac{1}{2} (A_i P(2) B_i + A_i P(2)^T B_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j P(2) D_i + C_j P(2)^T D_i) \rangle = \langle Q(1), \sum_{i=1}^{p} \frac{1}{2} (A_i (S(2) + \lambda(1) P(1) B_i + A_i (S(2) + \lambda(1) P(1))^T B_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j (S(2) + \lambda(1) P(1)^T D_i) + C_j (S(2) + \lambda(1) P(1)) D_i) \rangle = \lambda(1) \|Q(1)\|^2 + \langle Q(1), \sum_{i=1}^{p} \frac{1}{2} (A_i S(2) B_i + A_i S(2)^T B_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j S(2) D_i + C_j S(2)^T D_i) \rangle = \lambda(1) \|Q(1)\|^2 + \langle Q(1), \sum_{i=1}^{p} \frac{1}{2} (A_i^H Q(1) B_i^T + \overline{B}_i Q(1) A_i^T) + \sum_{j=1}^{t} \frac{1}{2} (C_j^H Q(1) D_i^T + D_i^T Q(1) C_j) \rangle = \lambda(1) \|Q(1)\|^2 - \frac{1}{\pi(1)} \langle S(2) - S(1), S(2) - S(1) \rangle = 0,
\]

and

\[
\langle P(1), S(2) \rangle = \langle S(1), S(2) \rangle = 0.
\]

Step 2: In this case, for $u < v < r$ we assume that

\[
\langle S(u), S(w) \rangle = 0, \quad \langle Q(u), Q(w) \rangle = 0, \quad \langle P(u), S(w) \rangle = 0.
\]
Therefore, one can obtain

$$\langle S(u), S(w + 1) \rangle$$

$$= \langle S(u), S(w) - \delta(w) \rangle \sum_{i=1}^{p} \frac{1}{2} (A_i^H Q(w) B_i^H + B_i Q(w)^T A_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j^H Q(w) D_j^H + D_j Q(w)^H C_j) \rangle$$

$$= -\delta(w) \langle S(u), \sum_{i=1}^{p} \frac{1}{2} (A_i^H Q(w) B_i^H + B_i Q(w)^T A_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j^H Q(w) D_j^H + D_j Q(w)^H C_j) \rangle$$

$$= -\delta(w) \langle \sum_{i=1}^{p} \frac{1}{2} (A_i S(u) B_i + A_i S(u)^T B_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j S(u) D_j + C_j S(u)^H D_j), Q(w) \rangle$$

$$= -\delta(w) \langle \sum_{i=1}^{p} \frac{1}{2} (A_i P(u) - \lambda (u - 1) P(u - 1)) B_i + A_i S(u)^T B_i \rangle$$

$$+ \sum_{j=1}^{t} \frac{1}{2} [C_j (P(u) - \lambda (u - 1) P(u - 1)) D_j + C_j (P(u) - \lambda (u - 1) P(u - 1)^H D_j), Q(w) \rangle$$

$$= -\delta(w) \langle Q(u) - \lambda (u - 1) Q(u - 1), Q(w) \rangle = 0,$$

$$\langle Q(u), Q(w + 1) \rangle$$

$$= \langle Q(u), \sum_{i=1}^{p} \frac{1}{2} (A_i S(w + 1) B_i + A_i S(w + 1)^T B_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j S(w + 1) D_j + C_j S(w + 1)^H D_j) \rangle$$

$$= \langle Q(u), \sum_{i=1}^{p} \frac{1}{2} [A_i (S(w + 1) + \lambda (w) P(w)) B_i + A_i (S(w + 1) + \lambda (w) P(w))^T B_i \rangle$$

$$+ \sum_{j=1}^{t} \frac{1}{2} [C_j (S(w + 1) + \lambda (w) P(w)) D_j + C_j (S(w + 1) + \lambda (w) P(w)^H D_j) \rangle$$

$$= \langle Q(u), \sum_{i=1}^{p} \frac{1}{2} (A_i S(w + 1) B_i + A_i S(w + 1)^T B_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j S(w + 1) D_j + C_j S(w + 1)^H D_j) \rangle$$

$$= \langle \sum_{i=1}^{p} \frac{1}{2} (A_i^H Q(u) B_i^H + B_i Q(u)^T A_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j^H Q(u) D_j^H + D_j Q(u)^H C_j), S(w + 1) \rangle$$

$$= -\frac{1}{\pi(n)} \langle S(u + 1) - S(u), S(w + 1) \rangle = 0,$$

and

$$\langle P(u), S(w + 1) \rangle$$

$$= \langle P(u), S(w) - \delta(w) \rangle \sum_{i=1}^{p} \frac{1}{2} (A_i^H Q(w) B_i^H + B_i Q(w)^T A_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j^H Q(w) D_j^H + D_j Q(w)^H C_j) \rangle$$

$$= -\delta(w) \langle P(u), \sum_{i=1}^{p} \frac{1}{2} (A_i^H Q(w) B_i^H + B_i Q(w)^T A_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j^H Q(w) D_j^H + D_j Q(w)^H C_j) \rangle$$

$$= -\delta(w) \langle \sum_{i=1}^{p} \frac{1}{2} (A_i P(w) B_i + A_i P(w)^T B_i) + \sum_{j=1}^{t} \frac{1}{2} (C_j P(w) D_j + C_j P(w)^H D_j), Q(w) \rangle$$

$$= -\delta(w) \langle Q(u), Q(w) \rangle = 0,$$
For \( u = w \), one has

\[
\langle S(w), S(w + 1) \rangle
= \langle S(w), S(w) - \delta(w)(\sum_{i=1}^{p} \frac{1}{2}(A_i^H Q(w)B_i^H + \overline{B}_i Q(w)A_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j^H \overline{Q}(w)D_j^H + D_j Q(w)^H C_j)) \rangle
\]

\[
= \|S(w)\|^2 - \delta(w)\langle S(w), \sum_{i=1}^{p} \frac{1}{2}(A_i^H Q(w)B_i^H + \overline{B}_i Q(w)A_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j^H \overline{Q}(w)D_j^H + D_j Q(w)^H C_j) \rangle
\]

\[
= \|S(w)\|^2 - \delta(w)\left( \sum_{i=1}^{p} \frac{1}{2}(A_i S(w)B_i + \sum_{j=1}^{t} C_j S(w)D_j, Q(w)) \right)
\]

\[
= \|S(w)\|^2 - \delta(w)\sum_{i=1}^{p} \frac{1}{2}(A_i S(w)B_i + A_i S(w)^T B_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j S(w)D_j + C_j S(w)^H D_j), Q(w))
\]

\[
= \|S(w)\|^2 - \delta(w)\sum_{i=1}^{p} \frac{1}{2}(A_i (P(w) - \lambda(w-1)P(w-1))B_i + A_i (P(w) - \lambda(w-1)P(w-1))^T B_i)
\]

\[
+ \sum_{j=1}^{t} \frac{1}{2}(C_j (P(w) - \lambda(w-1)P(w-1))D_j + C_j (P(w) - \lambda(w-1)P(w-1)^H D_j), Q(w))
\]

\[
= \|S(w)\|^2 - \delta(w)\langle Q(w) - \lambda(w-1)Q(w-1), Q(w) \rangle = 0,
\]

\[
\langle Q(w), Q(w + 1) \rangle
= \langle Q(w), \sum_{i=1}^{p} \frac{1}{2}(A_i P(w + 1)B_i + A_i P(w)^T B_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j P(w)D_j + C_j P(w)^H D_j) \rangle
\]

\[
= \langle Q(w), \sum_{i=1}^{p} \frac{1}{2}[A_i (S(w + 1) + \lambda(w)P(w))B_i + A_i (S(w + 1) + \lambda(w)P(w))^T B_i] + \sum_{j=1}^{t} \frac{1}{2}(C_j (S(w + 1) + \lambda(w)P(w))D_j + C_j (S(w + 1)^H D_j) + \lambda(w)Q(w)) \rangle
\]

\[
= \lambda(w)\|Q(w)\|^2 + \langle Q(w), \sum_{i=1}^{p} \frac{1}{2}(A_i (S(w + 1)B_i + A_i (S(w + 1)^T B_i)
\]

\[
+ \sum_{j=1}^{t} \frac{1}{2}(C_j (S(w + 1)D_j + C_j (S(w + 1)^H D_j) + \lambda(w)Q(w)) \rangle
\]

\[
= \lambda(w)\|Q(w)\|^2 + \sum_{i=1}^{p} \frac{1}{2}(A_i^H Q(w)B_i^H + \overline{B}_i Q(w)^H A_i) + \sum_{j=1}^{t} \frac{1}{2}(C_j^H Q(w)D_j^H + D_j Q(w)^H C_j), S(w + 1))
\]

\[
= \lambda(w)\|Q(w)\|^2 - \frac{1}{\delta(s)}\langle S(w + 1) - S(w), S(w + 1) \rangle
\]

\[
= \lambda(w)\|Q(w)\|^2 - \frac{1}{\delta(s)}\|S(w + 1)\|^2 = 0,
\]
and
\[
\langle P(w), S(w + 1) \rangle
\]
\[
= \langle P(w), S(w) - \delta(w) \rangle \sum_{i=1}^{p} \left( \frac{1}{2}(A_i^H \Theta(w) B_i^H + \Xi \Theta(w)^T A_i) + \sum_{j=1}^{l} \frac{1}{2}(C_j^H \Theta(w) D_j^H + D_j \Theta(w)^H C_j) \right)
\]
\[
= \langle S(w) + \lambda(w - 1) S(w - 1) + \lambda(w - 2) S(w - 2) + \cdots + \lambda(w - l) S(w - l) \rangle, \lambda(1) S(1), S(w) \rangle
\]
\[
- \delta(w) P(w), \sum_{i=1}^{p} \left( \frac{1}{2}(A_i^H \Theta(w) B_i^H + \Xi \Theta(w)^T A_i) + \sum_{j=1}^{l} \frac{1}{2}(C_j^H \Theta(w) D_j^H + D_j \Theta(w)^H C_j) \right)\]
\[
= \|S(w)\|^2 - \delta(w) \sum_{i=1}^{p} \left( \frac{1}{2}(A_i P(w) B_i + A_i P(w)^T B_i) + \sum_{j=1}^{l} \frac{1}{2}(C_j P(w) D_j + C_j P(w)^H D_j), Q(w) \right) \]
\[
= \|S(w)\|^2 - \delta(w) Q(w), Q(w) = 0.
\]

By the principle of induction, we draw the conclusion. □

**Theorem 1.** For algorithm 1, if there exists a positive number \( l \) such that \( \delta(l) = 0 \) or \( \delta(l) = \infty \), then \( X(l) \) is a solution of Problem 1.

**Proof.** If \( \delta(l) = 0 \), we have \( \|S(l)\|^2 = 0 \); If \( \delta(l) = \infty \), we have \( \|Q(l)\|^2 = 0 \). Hence, one can obtain
\[
\|S(l)\|^2 = \langle S(l) + \lambda(l - 1) S(l - 1) + \lambda(l - 2) S(l - 2) + \cdots + \lambda(l - 1) S(1), S(l) \rangle
\]
\[
= \langle P(l), S(l) \rangle
\]
\[
= \langle P(l), \sum_{i=1}^{p} \left( \frac{1}{2}(A_i^H R(l) B_i^H + \Xi R(l)^T A_i) + \sum_{j=1}^{l} \frac{1}{2}(C_j^H R(l) D_j^H + D_j R(l)^H C_j) \right) \rangle
\]
\[
= \sum_{i=1}^{p} \left( \frac{1}{2}(A_i P(l) B_i + A_i P(l)^T B_i) + \sum_{j=1}^{l} \frac{1}{2}(C_j P(l) D_j + C_j P(l)^H D_j), R(l) \right)
\]
\[
= 0.
\]
Thus, for \( \delta(l) = 0 \) or \( \delta(l) = \infty \) one has
\[
S(l) = \sum_{i=1}^{p} \left( \frac{1}{2}(A_i^H R(l) B_i^H + \Xi R(l)^T A_i) + \sum_{j=1}^{l} \frac{1}{2}(C_j^H R(l) D_j^H + D_j R(l)^H C_j) \right) = 0.
\]
So by Lemma 2 we can conclude that \( X(l) \) is the solution of Problem 1. □

**Theorem 2.** If the matrix equation (1.1) is consistent, then, for any arbitrary initial matrix \( X(l) \), the solution \( X^* \) of the Problem 1 can be obtained by using Algorithm 1 within a finite number of iterations in the absence of roundoff errors.

**Proof.** By Lemma 4, the set \( S(i), i = 1, 2, 3, \ldots, m \times n \) is an orthogonal basis of the real inner product space \( C^{m \times n} \) with dimension \( m \times n \). Therefore, we can obtain \( \|S(m \times n)\| = 0 \). It is also showed that \( X(m \times n + 1) \) is the solution of Problem 1 in the absence of roundoff errors. □

**Theorem 3.** Let the initial matrix be \( \sum_{i=1}^{p} \left( \frac{1}{2}(A_i^H F(l) B_i^H + \Xi F(l)^T A_i) + \sum_{j=1}^{l} \frac{1}{2}(C_j^H F(l) D_j^H + D_j F(l)^H C_j) \right) \), in which \( F(1) \in C^{m \times n} \) is an arbitrary symmetric matrix, or especially \( X(1) = 0 \), then the solution \( X^* \) generated by Algorithm 1 is the symmetric least norm solution of Problem 1.

**Proof.** Supposed that the initial matrix is
\[
X(1) = \sum_{i=1}^{p} \left( \frac{1}{2}(A_i^H F(l) B_i^H + \Xi F(l)^T A_i) + \sum_{j=1}^{l} \frac{1}{2}(C_j^H F(l) D_j^H + D_j F(l)^H C_j) \right).
\]
then by Algorithm 1 the generated matrix $X(k)$ can be easily expressed as

$$X(k) = \sum_{i=1}^{p} \frac{1}{2} (A_i^H F(k) B_i^H + B_i F(k)^T A_i) + \sum_{j=1}^{i} \frac{1}{2} (C_j^H F(k) D_j^H + D_j F(k)^T C_j),$$

for certain matrices $F(k) \in \mathbb{C}^{m \times n}$ for $k = 2, 3, \ldots$. It is showed that there exists a matrix $F^* \in \mathbb{C}^{m \times n}$ such that

$$X^* = \sum_{i=1}^{p} \frac{1}{2} (A_i F^* B_i^H + B_i (F^*)^T A_i) + \sum_{j=1}^{i} \frac{1}{2} (C_j^H F^* D_j^H + D_j (F^*)^T C_j).$$

Now if let $\tilde{X}^*$ is an arbitrary solution of Problem 1, then it is followed from Lemma 3 that there exists the matrix $Z^* \in \mathbb{C}^{m \times n}$ such that

$$\tilde{X}^* = X^* + Z^*,$$

and

$$\sum_{i=1}^{p} \frac{1}{2} (A_i Z^* B_i + A_i (Z^*)^T B_i) + \sum_{j=1}^{i} \frac{1}{2} (C_j Z^* D_j + C_j (Z^*)^T D_j) = 0.$$

Thus, we have

$$\langle X^*, Z^* \rangle = \langle \sum_{i=1}^{p} \frac{1}{2} (A_i^H F^* B_i^H + B_i (F^*)^T A_i) + \sum_{j=1}^{i} \frac{1}{2} (C_j^H F^* D_j^H + D_j (F^*)^T C_j), Z^* \rangle$$

$$\quad = \langle F^*, \sum_{i=1}^{p} \frac{1}{2} (A_i Z^* B_i + A_i (Z^*)^T B_i) + \sum_{j=1}^{i} \frac{1}{2} (C_j Z^* D_j + C_j (Z^*)^T D_j) \rangle = 0.$$  \hfill (3.10)

Therefore, according to the above Eq.(3.10), it is showed that

$$||\tilde{X}^*||^2 = ||X^* + Z^*||^2 = ||X^*||^2 + \|Z^*\|^2 + 2\langle X^*, Z^* \rangle = ||X^*||^2 + ||Z^*||^2 \geq ||X^*||^2.$$

This can be showed that the solution $X^*$ is the symmetric least Frobenius norm solution of Problem 1. \hfill \Box

Similar to [34], the minimization property of the proposed algorithm is stated as follows. This property shows that Algorithm 1 converges smoothly.

**Theorem 3.** For any initial symmetric matrix $X(1) \in \mathbb{C}^{m \times n}$, we have

$$\|\sum_{i=1}^{p} \frac{1}{2} (A_i X(k + 1) B_i + A_i X(k + 1)^T B_i) + \sum_{j=1}^{i} \frac{1}{2} (C_j X(k + 1) D_j + C_j X(k + 1)^H D_j) - E\|^2$$

$$= \min_{X \in \psi_k} \|\sum_{i=1}^{p} \frac{1}{2} (A_i X B_i + A_i X^T B_i) + \sum_{j=1}^{i} \frac{1}{2} (C_j X D_j + C_j X^H D_j) - E\|^2,$$  \hfill (3.11)

where $X(k + 1)$ is generated by Algorithm 1 at the $k + 1$-th iteration and $\psi_k$ presents an affine subspace which has the following form

$$\psi_k = X(1) + \text{span}(P(1), P(2), \ldots, P(k)).$$  \hfill (3.12)

**Proof.** For any matrix $X \in \psi_k$, it follows from Eq.(3.12) that there exist numbers $\alpha_1, \alpha_2, \ldots, \alpha_k$ such that

$$X = X(1) + \sum_{l=1}^{k} \alpha_l P(l).$$  \hfill (3.13)
Now we define the continuous and differentiable function $f$ with respect to the variable $\alpha_1, \alpha_2, \ldots, \alpha_k$ as

$$f(\alpha_1, \alpha_2, \ldots, \alpha_k) = \| \sum_{i=1}^{p} \frac{1}{2} \left[ A_i(X(1) + \sum_{l=1}^{k} \alpha_l P(l) )B_i + A_i(X(1) + \sum_{l=1}^{k} \alpha_l P(l) )^T B_i \right] \\
+ \sum_{j=1}^{k} \frac{1}{2} [ C_j(X(1) + \sum_{l=1}^{k} \alpha_l P(l) )D_j + C_j(X(1) + \sum_{l=1}^{k} \alpha_l P(l) )^T D_j ] - E \|^2.$$

According to Lemma 4, we have

$$f(\alpha_1, \alpha_2, \ldots, \alpha_k) = \| \sum_{i=1}^{p} \frac{1}{2} (A_iX(1)B_i + A_iX(1)^T B_i) + \sum_{j=1}^{k} \frac{1}{2} (C_jX(1)^T D_j + C_jX(1)D_j) - E \\
+ \sum_{l=1}^{k} \alpha_l \left[ \sum_{i=1}^{p} \frac{1}{2} (A_iP(l)B_i + A_iP(l)^T B_i) + \sum_{j=1}^{k} \frac{1}{2} (C_jP(l)D_j + C_jP(l)^T D_j) \right] \|^2 \\
= \| R(1) \|^2 + \sum_{l=1}^{k} \alpha_l^2 \| Q(l) \|^2 - 2 \alpha_l \langle Q(l), R(1) \rangle.$$

Now we consider the problem of minimizing the function $f(\alpha_1, \alpha_2, \ldots, \alpha_k)$. It is obvious that

$$\min_{\alpha_l} f(\alpha_1, \alpha_2, \ldots, \alpha_k) = \min_{\alpha_l} \| \sum_{i=1}^{p} \frac{1}{2} (A_iX(1)B_i + A_iX(1)^T B_i) + \sum_{j=1}^{k} \frac{1}{2} (C_jX(1)^T D_j + C_jX(1)D_j) - E \|^2.$$

For this function, the minimum occurs when

$$\frac{\partial f(\alpha_1, \alpha_2, \ldots, \alpha_k)}{\partial \alpha_l} = 0 \text{ for } l = 1, 2, \ldots, k.$$

Thus, we can get

$$\alpha_l = \frac{\langle Q(l), R(1) \rangle}{\| Q(l) \|^2}.$$

By Algorithm 1, one can obtain

$$R(1) = R(l) + \delta(l - 1)Q(l - 1) + \delta(l - 2)Q(l - 2) + \cdots + \delta(1)Q(1).$$

Therefore, it follows from Lemma 4 that

$$\alpha_l = \frac{\langle Q(l), R(l) \rangle}{\| Q(l) \|^2} = \frac{\langle Q(l), R(0) \rangle + \sum_{i=1}^{p} \frac{1}{2} (A_iX(1)B_i + A_iX(1)^T B_i) + \sum_{j=1}^{k} \frac{1}{2} (C_jX(1)^T D_j + C_jX(1)D_j) \rangle}{\| Q(l) \|^2} \\
= \frac{\langle Q(l), S(l) \rangle}{\| Q(l) \|^2} = \frac{\langle S(l), \delta(l - 1)P(l - 1)S(l) \rangle}{\| Q(l) \|^2} \\
= \frac{\| S(l) \|^2}{\| Q(l) \|^2} = \delta(l).$$

Thus, the proof has been completed. □

By Theorem 1, the solution generalized by Algorithm 1 at the $k + 1$–th iteration for any initial matrix minimizes the residual norm in the affine subspace $\psi_k$. Also one has

$$\| \sum_{i=1}^{p} \frac{1}{2} (A_iX(k + l)B_i + A_iX(k + l)^T B_i) + \sum_{j=1}^{k} \frac{1}{2} (C_jX(k + l)^T D_j + C_jX(k + l)D_j) - E \|^2 \\
\leq \| \sum_{i=1}^{p} \frac{1}{2} (A_iX(k)B_i + A_iX(k)^T B_i) + \sum_{j=1}^{k} \frac{1}{2} (C_jX(k)^T D_j + C_jX(k)D_j) - E \|^2,$$
which shows that the sequence of the norm of residuals $\|R(1)\|, \|R(2)\|, \cdots$ is monotonically decreasing. This decent property of the norm of the residuals shows that Algorithm 1 processes fast and smoothly convergence.

In the following, we will solve Problem 2. For a given matrix $X_0$, one has

$$
\min_{X \in \mathbb{C}^{m \times n}} \| \sum_{i=1}^{p} \frac{1}{2} (A_i X B_i + A_i X^T B_i) + \sum_{j=1}^{m} \frac{1}{2} (C_j X D_j + C_j X^H D_j) - E \|
$$

$$
= \min_{X \in \mathbb{C}^{m \times n}} \| \sum_{i=1}^{p} \frac{1}{2} (A_i (X - X_0) B_i + A_i (X - X_0)^T B_i) + \sum_{j=1}^{m} \frac{1}{2} [C_j (X - X_0) D_j + C_j (X - X_0)^H D_j] - (E - \sum_{i=1}^{p} \frac{1}{2} (A_i X_0 B_i + A_i X_0^T B_i) - \sum_{j=1}^{m} \frac{1}{2} (C_j X_0 D_j + C_j X_0^H D_j)) \|
$$

(3.15)

If we denote the set

$$
E_1 = E - \sum_{i=1}^{p} \frac{1}{2} (A_i X_0 B_i + A_i X_0^T B_i) - \sum_{j=1}^{m} \frac{1}{2} (C_j X_0 D_j + C_j X_0^H D_j)
$$

and let

$$
X_1 = X - X_0,
$$

then Problem 2 is equivalent to find the least Frobenius norm solution $X_1^*$ of

$$
\min_{X_1 \in \mathbb{C}^{m \times n}} \| \sum_{i=1}^{p} \frac{1}{2} (A_i X_1 B_i + A_i X_1^T B_i) + \sum_{j=1}^{m} \frac{1}{2} (C_j X_1 D_j + C_j X_1^H D_j) - E_1 \|
$$

(3.16)

which can be computed by using Algorithm 1 with the initial matrix

$$
X_1(1) = \sum_{i=1}^{p} \frac{1}{2} (A_i^H F B_i^T + B_i^T F^T A_i) + \sum_{j=1}^{m} \frac{1}{2} (C_j^H F D_j^T + D_j^T F^H C_j),
$$

where $F \in \mathbb{C}^{m \times n}$ is an arbitrary matrix, or especially $X_1(1) = 0$. Thus the solution of Problem 2 can be stated as

$$
\hat{X} = X_1^* + X_0.
$$

(3.17)

4. Numerical examples

In this section, two numerical examples are presented to illustrate the efficiency of Algorithm 1.

**Example 4.1.** Find the symmetric least Frobenius norm solution of the following generalized sylvester-conjugate matrix equation

$$
AXB + CXD = M,
$$

(4.1)

where

$$
A = \begin{bmatrix}
1 + 2i & 13 - i & 6 + i & 4 + 3i \\
2 + i & 0 & 12 & 10 \\
5 + 6i & 2 - 3i & 11 - 2i & i \\
1 & 12 & 0 & 9i
\end{bmatrix},
B = \begin{bmatrix}
2 & 3 - 12i & 4 + 6i & 9 + 8i \\
46i & 11 & 12 & 9 + 18i \\
0 & 12 & 15 & 18 \\
2i & -9i & 12 & 11
\end{bmatrix},
$$

$$
C = \begin{bmatrix}
i & 9 & 1 - 5i & 2i \\
11 & 2 - 13i & 12 & 11 \\
1 + 8i & 11 - 2i & 21 & i \\
9 + 8i & 11 & i & 8 + i
\end{bmatrix},
D = \begin{bmatrix}
9 + 2i & 2 - i & 2i & 6 + 8i \\
4i & 19 & 20 & 11 \\
23 & 26 + 3i & 9i & 9 \\
23 & 0 & 16 & 8i
\end{bmatrix},
$$

$$
M = \begin{bmatrix}
2 & 3 - 12i & 4 + 6i & 9 + 8i \\
46i & 11 & 12 & 9 + 18i \\
0 & 12 & 15 & 18 \\
2i & -9i & 12 & 11
\end{bmatrix}.
$$
The relative errors of solution are presented in figure 3 and figure 4, where

Find the symmetric least Frobenius norm solution of the following matrix equation

Example 4.2.

It can be verified that the generalized Sylvester-conjugate matrix equation (4.1) are consistent and have the solution

The residual of solution are presented in figure 1 and figure 2, where

Applying Algorithm 1, if we let the initial matrix \( X(0) = zeros(4,4) \), \( X(0) = 10 \times I_4 \) and \( X(0) = 10 \times ones(4,4) \) respectively, we have the solution to the equation (4.1)

with corresponding residual

The residual of solution are presented in figure 1 and figure 2, where

The relative errors of solution are presented in figure 3 and figure 4, where

Example 4.2. Find the symmetric least Frobenius norm solution of the following matrix equation

where

\[
A = \begin{pmatrix}
112i & 13 - 79i & 6 + 34i & 43 + 31i \\
21 + 2i & 110 & 12 & 10 \\
5 + 6i & 2 - 23i & 113 - 2i & i \\
13 & 152 & 0 & 59i
\end{pmatrix},
\]

\[
B = \begin{pmatrix}
255 & 35 - 152i & 45 + 65i & 95 + 85i \\
46i & 151 & 152 & 95 + 58i \\
0 & 512 & 155 & 185 \\
2i & -95i & 125 & 118
\end{pmatrix},
\]

\[
C = \begin{pmatrix}
16i & 4 + 9i & 2 + 123i & 69i \\
-28 + 9i & 2 + 8i & 6 & 178 \\
31 & 228 & 1 - i & 6 + 9i \\
2 & 3 & 15 & 29i
\end{pmatrix},
\]

\[
D = \begin{pmatrix}
2 - 9i & 111 & 3 & 1 - 78i \\
4 & 3 + 2i & 2 & 6 + 90i \\
4 & 2 & 390i & 1 \\
1 & 22 & 130i & 0
\end{pmatrix},
\]

\[
E = \begin{pmatrix}
34i & 9 - 9i & 13 - 54i & 21i \\
118 & 27 - 13i & 572 & 11 - 78i \\
188i & 110 - 2i & 21 - 96i & i \\
96 + 8i & 11i & i & 86 + i
\end{pmatrix},
\]

\[
F = \begin{pmatrix}
96 + 2i & 26 - i & 26i & 66 + 84i \\
446i & 169 & 260 & 116 \\
23 & 26 + 63i & 97i & 97 \\
237 & 0 & 17 - 9i & 8 - 56i
\end{pmatrix},
\]

\[
M = \begin{pmatrix}
104 + 7572i & 9059 - 1126i & 7465 + 3237i & 6522 + 7607i \\
6409 - 816i & 11016 - 10231i & 11011 - 833i & 9606 + 5155i \\
7700 + 9199i & 12752 - 4698i & 13886 + 1860i & 9900 + 7479i \\
7484 + 6793i & 13561 + 3984i & 5700 + 4557i & 6483 + 7741i
\end{pmatrix},
\]
Figure 1: The residual of solution for Example 4.1

Figure 2: The residual of solution for Example 4.1
Figure 3: The relative error of solution for Example 4.1

Figure 4: The relative error of solution for Example 4.1
It can be verified that the generalized Sylvester-conjugate matrix equation (4.2) are consistent and have the solution
\[
X = \begin{pmatrix}
24 + 13i & 22 + i & 11i & 6 \\
22 + i & 21 + 2i & 19 + 16i & 10 \\
11i & 19 + 16i & 2i & 17 \\
6 & 10 & 17 & 12i
\end{pmatrix}.
\]

Let the initial matrix \(X(0) = \text{zeros}(4, 4), X(0) = 10 \times I_4\) and \(X(0) = 10 \times \text{ones}(4, 4)\) respectively, by applying Algorithm 1 we obtain the solution.

The residual of solution are presented in figure 5 and figure 6, where
\[
r(k) = \log_{10}\|M - AX(k)B - CX(k)D\|.
\]

The relative errors of solution are presented in figure 7 and figure 8, where
\[
err(k) = \frac{\|X(k) - X\|}{\|X\|}.
\]

\[
X(32) = \begin{pmatrix}
24.0000 + 12.9999i & 22.0000 + 0.9999i & 11.0000i & 5.9999 \\
22.0000 + 1.0000i & 21.0000 + 1.9999i & 19.0000 + 16.0000i & 10.0000 \\
11.0000i & 19.0000 + 16.0000i & 2.0000i & 17.0000 \\
5.9999 & 9.9999 & 17.0000 & 12.0000i
\end{pmatrix}
\]

with corresponding residual
\[
r(32) = 1.3075 \times 10^{-9}.
\]
\[
err(32) = 8.1374 \times 10^{-16}.
\]

**Remark 1.** From the two examples above, it is showed that the Algorithm 1 is very efficient for any initial symmetric matrices. Our proposed iterative method can obtain the symmetric least squares Frobenius norm solution within finite iteration steps in the absence of roundoff errors for any initial symmetric matrices.
Figure 6: The residual of solution for Example 4.2

Figure 7: The relative error of solution for Example 4.2
5. Conclusions

In this paper, by extending the CGLS iterative algorithm, we propose the modified CGLS iterative algorithm (MCGLS) to solve the symmetric least squares solution of generalized Sylvester-conjugate matrix equation (1.1). For any initial symmetric matrix $X(1)$, by the proposed MCGLS iterative algorithm, symmetric least Frobenius norm solution $X^*$ can be obtained in finite iteration steps in the absence of roundoff errors. Moreover, by using this MCGLS iterative method, the optimal approximation solution $\tilde{X}$ to a given matrix $X_0$ can be derived by first finding the symmetric least Frobenius norm solution of a new corresponding matrix equation. This iterative algorithm can be adapted to solve different classes linear matrix equations. Two numerical examples are offered to illustrate the effectiveness of the proposed algorithm.

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