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CONJUGATE GRADIENT-TYPE METHODS FOR LINEAR SYSTEMS WITH COMPLEX SYMMETRIC COEFFICIENT MATRICES*

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Abstract. Conjugate gradient-type methods for the solution of large sparse linear systems $Ax = b$ with complex symmetric coefficient matrices $A = A^T$ are considered. Such linear systems arise in important applications, such as the numerical solution of the complex Helmholtz equation. Furthermore, most complex non-Hermitian linear systems which occur in practice are actually complex symmetric. Conjugate gradient-type iterations which are based on a variant of the nonsymmetric Lanczos algorithm for complex symmetric matrices are investigated. In particular, a new approach with iterates defined by a quasi-minimal residual property is proposed. The resulting algorithm presents several advantages over the standard biconjugate gradient method. Some remarks are also included on the obvious approach to general complex linear systems by solving equivalent real linear systems for the real and imaginary parts of x. Finally, numerical experiments for linear systems arising from the complex Helmholtz equation are reported.

Key words. complex symmetric matrices, nonsymmetric Lanczos algorithm, biconjugate gradients, minimal residual property

AMS(MOS) subject classifications. 65F10, 65N20

1. Introduction.

Conjugate gradient-type methods—used in combination with preconditioning—are among the most effective iterative procedures for solving large sparse nonsingular systems of linear equations

$$Ax = b. \tag{1.1}$$

The archetype of these schemes is the classical conjugate gradient algorithm (CG hereafter) of Hestenes and Stiefel [24] for Hermitian positive definite matrices A.

While most linear systems that arise in practice have real coefficient matrices A and real right-hand sides b, there are some important applications (see [16] and the references therein) that lead to complex linear systems. Partial differential equations that model dissipative processes usually involve complex coefficient functions and/or complex boundary conditions (see, e.g., [29]), and discretizing them yields linear systems with complex matrices A. A typical example for this category is the complex Helmholtz equation

$$-\Delta u - \sigma_1 u + i\sigma_2 u = f, \tag{1.2}$$

where σ_1, σ_2 are real coefficient functions, which describes the propagation of damped time-harmonic waves as, e.g., electromagnetic waves in conducting media. Further applications, which give rise to complex linear systems, include discretizations of the time-dependent Schrödinger equation using implicit difference schemes, inverse

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scattering problems, underwater acoustics, eddy current computations [2], numerical computations in quantum chromodynamics, and numerical conformal mapping.

In all these examples, the resulting coefficient matrices A are non-Hermitian. However, they still exhibit special structures. Often, A differs from a Hermitian matrix only by a shift and a rotation:

$$A = e^{i\theta}(T + i\sigma I), \quad T = T^H \text{ Hermitian}, \quad \sigma \in \mathbb{C},\ \theta \in \mathbb{R}, \quad i := \sqrt{-1}. \tag{1.3}$$

In almost all other cases, which lead to complex systems, the coefficient matrix is symmetric:

$$A = A^T \text{ is complex symmetric.} \tag{1.4}$$

Note that the two families (1.3) and (1.4) overlap. The matrix (1.3) is complex symmetric if and only if T is real.

Surprisingly, when complex linear systems (1.1) are solved in practice, usually no attempt is made to exploit the special structures (1.3) or (1.4). Indeed, there are two popular approaches. The first one (see, e.g., [1]) is to apply preconditioned CG to the Hermitian positive definite normal equations

$$A^H A x = A^H b. \tag{1.5}$$

Of course, complex numbers can always be avoided by rewriting (1.1) as a real linear system for the real and imaginary parts of x. The second popular approach is to solve this real and, in general, nonsymmetric linear system by one of the generalized CG methods such as GMRES [40]. It turns out that in both cases the resulting iterative schemes tend to converge slowly. As a consequence, complex linear systems have the bad reputation of being difficult to solve by CG-type methods. On the other hand, for the class of shifted Hermitian matrices (1.3), there are efficient CG-type algorithms [10], [11], [28], [16] for complex linear systems in their original form (1.1). We refer the reader to [16] for a detailed study and practical aspects of these schemes. In [16] it is also shown how the special structure (1.3) can be preserved by using polynomial preconditioning.

In this paper, we are mainly concerned with CG-type methods for linear systems (1.1) with coefficient matrices of the second class (1.4). In particular, we consider approaches based on a variant of the nonsymmetric Lanczos algorithm, which was successfully used for computing eigenvalues of complex symmetric matrices (see [35] and [6, Chap. 6]). This Lanczos recursion generates basis vectors for the Krylov subspace induced by A that are orthogonal with respect to a certain indefinite inner product. The standard way to obtain from this basis iterates, which approximate the exact solution of (1.1), is to enforce a biconjugate gradient (BCG hereafter) condition. Here, we propose a new approach that generates iterates via a quasi-minimal residual property. On typical examples, the resulting algorithm displays better convergence properties than the BCG approach. In particular, it produces residuals whose norms are almost monotonically decreasing, in contrast to the erratic convergence behavior that is typical for BCG. Moreover, the new technique eliminates one of the two sources of possible breakdown in the BCG approach.

The outline of the paper is as follows. In §2, we review the Lanczos recursion and related algorithms for complex symmetric matrices. Also, some theoretical properties which will be needed later on are listed. In §3, we propose the quasi-minimal residual approach for complex symmetric matrices. Section 4 contains some remarks on the problem of breakdown of the complex symmetric Lanczos recursion. In §5, we are concerned with the issue of "complex versus equivalent real linear systems." In particular,

some results are presented which indicate that for Krylov subspace methods, such as CG-type algorithms, it is always preferable to solve the original complex system rather than equivalent real ones. In §6, some typical results of numerical experiments for linear systems arising from finite difference approximations to the complex Helmholtz equation (1.2) are given. Finally, in §7, we make some concluding remarks.

Throughout the paper, all vectors and matrices, unless stated otherwise, are assumed to be complex. As usual, $\overline{M} = [\overline{m_{jk}}]$, $M^T = [m_{kj}]$, and $M^H = \overline{M}^T$ denote the complex conjugate, transpose, and Hermitian matrix, respectively, corresponding to the matrix $M = [m_{jk}]$. Moreover, we set $\operatorname{Re} M = (M + \overline{M})/2$ and $\operatorname{Im} M = (M - \overline{M})/(2i)$ for its real and imaginary part, respectively. The notation

$$K_k(c, B) := \operatorname{span}\{c, Bc, \cdots, B^{k-1}c\}$$

is used for the kth Krylov subspace of $\mathbb{C}^n$ generated by $c \in \mathbb{C}^n$ and the $n \times n$ matrix B. Furthermore, $\sigma(B)$ denotes the spectrum of B. The vector norm $\|x\| = \sqrt{x^H x}$ is always the Euclidean norm. The set of all complex polynomials of degree at most k is denoted by

$$\Pi_k := \{p(\lambda) \equiv \gamma_0 + \gamma_1\lambda + \cdots + \gamma_k\lambda^k \mid \gamma_0, \gamma_1, \cdots, \gamma_k \in \mathbb{C}\}.$$

Moreover, the coefficient matrix A of (1.1) is always $n \times n$ and, unless stated otherwise, assumed to be complex symmetric. Generally, $x_k \in \mathbb{C}^n$, $k = 0, 1, \cdots$, denote iterates for (1.1) with corresponding residual vectors $r_k := b - Ax_k$. If necessary, quantities of different algorithms will be distinguished by superscripts, e.g., x_k^{BCG} and x_k^{QMR}. Finally, an iterative scheme for solving (1.1) is called a Krylov subspace method if its iterates are of the form

$$x_k \in x_0 + K_k(r_0, A) \quad \text{or, equivalently,} \quad x_k = x_0 + P(A)r_0,\ P \in \Pi_{k-1}. \tag{1.6}$$

Note that, in particular, CG-type algorithms for (1.1) fall into this category.

2. The Lanczos recursion and related algorithms for complex symmetric matrices. The Lanczos procedure [31] for general complex $n \times n$ matrices A consists of two three-term recurrences (see, e.g., [43, pp. 388–394]). As Lanczos pointed out [33, p. 176], the general method reduces to only one recursion if A is Hermitian, respectively, complex symmetric. In particular, for these two special cases, work and storage of the general Lanczos method are halved. The resulting Hermitian Lanczos recursion has been studied extensively (see [20, Chap. 9] and the references therein). In contrast, the literature on the complex symmetric variant is scarce and restricted to the application of the algorithm to computing eigenvalues of complex symmetric matrices (see Moro and Freed [35] and Cullum and Willoughby [6, Chap. 6]). Here we hope to convince the reader that the complex symmetric Lanczos algorithm is also very useful for solving linear systems.

2.1. The Lanczos recursion. The basic method is as follows:

ALGORITHM 2.1 (LANCZOS METHOD FOR $A = A^T$).

(1) *Start:*

- *Choose* $r_0 \in \mathbb{C}^n$, $r_0 \neq 0$;
- *Set* $\tilde{v}_1 = r_0$ *and* $v_0 = 0$.

(2) *For* $k = 1, 2, \cdots$ *do:*

- *Compute* $\beta_k = \left(\tilde{v}_k^T \tilde{v}_k\right)^{1/2}$;

- *If* $\beta_k = 0$*: Set* $m_0 = k - 1$*, and stop;*
- *Otherwise, set* $v_k = \tilde{v}_k / \beta_k$*;*
- *Compute* $\alpha_k = v_k^T A v_k$*;*
- *Set* $\tilde{v}_{k+1} = A v_k - \alpha_k v_k - \beta_k v_{k-1}$.

In the following proposition, some elementary properties of Algorithm 2.1 are listed; proofs can be found in [5, Chap. 6]. We set

$$V_k := [\, v_1 \quad v_2 \quad \dots \quad v_k \,] \quad \text{and} \quad T_k := \begin{bmatrix} \alpha_1 & \beta_2 & 0 & \dots & 0 \\ \beta_2 & \alpha_2 & \beta_3 & \ddots & \vdots \\ 0 & \beta_3 & \ddots & \ddots & 0 \\ \vdots & \ddots & \ddots & \ddots & \beta_k \\ 0 & \dots & 0 & \beta_k & \alpha_k \end{bmatrix}. \tag{2.1}$$

Moreover, $m_\star = m_\star(r_0, A) := \dim K_n(r_0, A)$ denotes the *grade* of r_0 with respect to A (cf. [43, p. 37]). We remark that $m_\star \geq 1$ is the smallest integer such that $K_{m_\star}$ is an A-invariant subspace of $\mathbb{C}^n$. Equivalently, if A is nonsingular and $r_0 = b - Ax_0$, $m_\star \geq 1$ is the smallest integer such that

$$A^{-1} b \in x_0 + K_{m_\star}(r_0, A). \tag{2.2}$$

PROPOSITION 2.2. (a) *In exact arithmetic, Algorithm* 2.1 *stops after a finite number of steps* $k = m_0 + 1$ *and* $0 \leq m_0 \leq m_\star$*. Furthermore,* $\tilde{v}_{m_0+1} = 0$ *if* $m_0 = m_\star$ (*"regular termination"*)*, and* $\tilde{v}_{m_0+1} \neq 0$ *if* $m_0 < m_\star$ (*"breakdown"*).

(b) *For* $k = 1, 2, \cdots, m_0$*:*

$$v_k^T v_j = \begin{cases} 0, & \text{if } k \neq j \\ 1, & \text{if } k = j \end{cases}, \quad j = 1, 2, \cdots, m_0, \tag{2.3}$$

$$K_k(r_0, A) = \operatorname{span}\{v_1, v_2, \cdots, v_k\}, \tag{2.4}$$

$$A V_k = V_k T_k + [\, 0 \quad 0 \quad \cdots \quad 0 \quad \tilde{v}_{k+1} \,]. \tag{2.5}$$

Notice that, by (2.3)–(2.4), the Lanczos vectors $v_1, \cdots, v_k$ form an orthonormal basis for $K_k(r_0, A)$ with respect to the indefinite bilinear form

$$(x, y) := y^T x, \quad x, y \in \mathbb{C}^n. \tag{2.6}$$

In particular, if Algorithm 2.1 terminates regularly, it generates a basis of the affine space $x_0 + K_{m_\star}(r_0, A)$, which, in view of (2.2), contains the exact solution of $Ax = b$.

Note that the indefinite bilinear form (2.6) is the proper (cf. Craven [5]) "inner product" for complex symmetric matrices. Unfortunately, it has the defect that there exist vectors $v \in \mathbb{C}^n$ which are *quasi-null* [5], i.e., $(v, v) = 0$, but $v \neq 0$. Consequently, it cannot be excluded that Algorithm 2.1 actually breaks down. Indeed, in view of part (a) of Proposition 2.2, a breakdown occurs if we encounter a quasi-null vector $\tilde{v}_k$. The phenomenon of breakdown will be discussed further in §4.

Finally, we remark that there is a close connection (see Theorem 2.4 in [15]) of the complex symmetric variant 2.1 with the Lanczos algorithm for general matrices. Unlike Hermitian matrices, complex symmetric matrices do not have any special spectral properties. Indeed (see, e.g., [25, Thm. 4.4.9]), any complex $n \times n$ matrix is similar to a complex symmetric matrix. This result entails that the general nonsymmetric Lanczos method differs from the complex symmetric Algorithm 2.1 only in an additional starting vector s_0, which can be chosen independently of r_0 in 2.1.

After these preliminaries, we now turn to linear systems (1.1). In the sequel, it is always assumed that A is nonsingular.

2.2. Related algorithms. In his celebrated papers [31], [32], Lanczos also proposed a scheme, closely related to the nonsymmetric Lanczos process, for solving general non-Hermitian linear systems, namely, the biconjugate gradient algorithm (BCG). We refer the reader to [12], [39], [26] for a detailed discussion of the BCG approach.

Like the nonsymmetric Lanczos method, BCG for general linear systems is started with two vectors: the residual $r_0 = b - Ax_0$ of the initial guess x_0 and a second vector $s_0 \neq 0$. We remark that s_0 is still unspecified. Due to the lack of a criterion for the choice of s_0, we usually set $s_0 = r_0$ in practice. For the case of complex symmetric matrices A, it is straightforward to show that, in analogy to the complex symmetric variant 2.1 of the general Lanczos process, the choice $s_0 = r_0$ results in a scheme which requires only half the work and storage of general BCG. The resulting procedure is as follows:

ALGORITHM 2.3. (BCG *for* $A = A^T$)

(1) *Start:*

- *Choose* $x_0 \in \mathbb{C}^n$;
- *Set* $p_0 = r_0 = b - Ax_0$ *and compute* $r_0^T r_0$.

(2) *For* $k = 1, 2, \cdots$ *do:*

- *Compute* Ap_{k-1} *and* $p_{k-1}^T Ap_{k-1}$;
- *If* $p_{k-1}^T Ap_{k-1} = 0$ *or* $r_{k-1}^T r_{k-1} = 0$: *Set* $m_1 = k - 1$, *and stop;*
- *Otherwise, set* $\delta_k = r_{k-1}^T r_{k-1} / p_{k-1}^T Ap_{k-1}$;
- *Compute* $x_k = x_{k-1} + \delta_k p_{k-1}$ *and* $r_k = r_{k-1} - \delta_k Ap_{k-1}$;
- *Compute* $r_k^T r_k$ *and set* $\rho_k = r_k^T r_k / r_{k-1}^T r_{k-1}$;
- *Compute* $p_k = r_k + \rho_k p_{k-1}$.

Note that the *transpose* in all dot products in Algorithm 2.3 is essential. In particular, Algorithm 2.3 is different from the classical CG method for positive definite matrices $A = A^H$.

In the sequel, BCG always refers to the complex symmetric Algorithm 2.3. Next, we list some basic properties of BCG that will be needed in subsequent sections. These results are immediate consequences of results (e.g., Jacobs [26]) for the general biconjugate gradient method.

PROPOSITION 2.4. (a) *In exact arithmetic, Algorithm* 2.3 *stops after a finite number of steps* $k = m_1 + 1$ *and* $0 \leq m_1 \leq m_\star$. *Furthermore,* $x_{m_1} = A^{-1}b$ *if* $m_1 = m_\star$ (*"regular termination"*), *and* $x_{m_1} \neq A^{-1}b$ *if* $m_1 < m_\star$ (*"breakdown"*).

(b) *For* $k = 1, 2, \cdots, m_1$:

$$r_{k-1}^T r_{j-1} = 0, \qquad k \neq j, \quad j = 1, 2, \cdots, m_1, \tag{2.7}$$

$$K_k(r_0, A) = \operatorname{span}\{r_0, r_1, \cdots, r_{k-1}\}. \tag{2.8}$$

(c) *Let* $k \in \{1, 2, \cdots, m_1\}$. *Then,* x_k *is uniquely determined by the Galerkin condition*

$$(b - Ax_k)^T y = 0 \quad \textit{for all} \quad y \in K_k(r_0, A), \quad x_k \in x_0 + K_k(r_0, A), \tag{2.9}$$

with respect to the inner product (2.6).

By comparing (2.7)–(2.8) with (2.3)–(2.4), we conclude that r_{k-1} is parallel to the Lanczos vector v_k generated by Algorithm 2.1. More precisely, we easily verify

that

$$r_{k-1} = (-1)^{k-1}\delta_1 \cdots \delta_{k-1}\beta_1 \cdots \beta_{k-1}\beta_k v_k, \quad k = 1, 2, \cdots, m_1. \tag{2.10}$$

Notice that there are two different causes for breakdown of Algorithm 2.3. The first one, namely, the occurrence of a quasi-null residual vector r_{k-1}, is, in view of (2.10), equivalent to the breakdown of the complex symmetric Lanczos Algorithm 2.1. In addition, Algorithm 2.3 breaks down if we encounter a search direction $p_{k-1} \neq 0$ with $p_{k-1}^T A p_{k-1} = 0$. This second cause of breakdown is more severe than the first one. As we will see in §3, it occurs if no Galerkin iterate (2.9) exists.

Closely related to the biconjugate gradient method for general linear systems (1.1) is the conjugate gradients squared algorithm (CGS hereafter) that was recently proposed by Sonneveld [41].

ALGORITHM 2.5. (CGS *for general* A)

(1) *Start:*

- *Choose* $x_0 \in \mathbb{C}^n$ *and* $s_0 \in \mathbb{C}^n$, $s_0 \neq 0$;
- *Set* $p_0 = u_0 = r_0 = b - Ax_0$ *and compute* $s_0^T r_0$.

(2) *For* $k = 1, 2, \cdots$ *do:*

- *Compute* Ap_{k-1} *and* $s_0{}^T A p_{k-1}$;
- *If* $s_0{}^T A p_{k-1} = 0$ *or* $s_0{}^T r_{k-1} = 0$: *Stop;*
- *Otherwise, set* $\alpha_k = s_0^T r_{k-1} / s_0^T A p_{k-1}$;
- *Compute* $q_k = u_{k-1} - \alpha_k A p_{k-1}$;
- *Compute* $x_k = x_{k-1} + \alpha_k(u_{k-1} + q_k)$ *and* $r_k = r_{k-1} - \alpha_k A(u_{k-1} + q_k)$;
- *Compute* $s_0^T r_k$ *and set* $\beta_k = s_0^T r_k / s_0^T r_{k-1}$;
- *Compute* $u_k = r_k + \beta_k q_k$ *and* $p_k = u_k + \beta_k(q_k + \beta_k p_{k-1})$.

Notice that, like general BCG, CGS has a second unspecified starting vector s_0. However, unlike BCG, even with the special choice $s_0 = r_0$, CGS cannot exploit the complex symmetry of A. In particular, for $A = A^T$, Algorithm 2.5 requires per iteration about twice as much work as the BCG Algorithm 2.3.

Finally, as a special case of the general connection [41] between the CGS and BCG approaches, we have the following result.

PROPOSITION 2.6. *Let* $A = A^T$, $r_0 = r_0^{\mathrm{BCG}} = r_0^{CGS}$, *and, in Algorithm* 2.5, $s_0 = r_0$. *Then, for* $k = 0, 1, \cdots, m_1$,

$$r_k^{\mathrm{BCG}} = p_k(A) r_0 \quad \textit{and} \quad r_k^{CGS} = \big(p_k(A)\big)^2 r_0$$

for some $p_k \in \Pi_k$ *with* $p_k(0) = 1$.

3. A quasi-minimal residual algorithm for complex symmetric matrices. In this section, we propose a new approach for solving complex symmetric linear systems. The method is based on the complex symmetric Lanczos Algorithm 2.1. For simplicity, we assume throughout this section that, in exact arithmetic, Algorithm 2.1 terminates regularly, i.e.,

$$\beta_k \neq 0 \quad \text{for} \quad k = 1, 2, \cdots, m_\star, \quad \beta_{m_\star + 1} = 0. \tag{3.1}$$

Moreover, always let $k \in \{1, 2, \cdots, m_\star\}$ in the following.

3.1. Basic approach. Let x_k be the kth iterate of any Krylov subspace method (1.6). Then, by (2.4) and with V_k as defined in (2.1), we have

$$x_k = x_0 + V_k z_k \quad \text{where} \quad z_k \in \mathbb{C}^k. \tag{3.2}$$

Using (2.5) and $r_0 = \beta_1 v_1$, it follows from (3.2) that

$$r_k = b - Ax_k = r_0 - AV_k z = \beta_1 v_1 - V_{k+1}\tilde{T}_k z_k = V_{k+1}\big(\beta_1 e_1 - \tilde{T}_k z_k\big). \tag{3.3}$$

Here, $e_1 := [1 \quad 0 \quad \cdots \quad 0]^T$ denotes the first unit vector,

$$\tilde{T}_k := \begin{bmatrix} T_k \\ \beta_{k+1} e_k^T \end{bmatrix} \quad \text{with} \quad e_k^T := [0 \quad \cdots \quad 0 \quad 1], \tag{3.4}$$

and, if $k = m_\star$, $v_{m_\star+1} := 0$. Recall that T_k was defined in (2.1).

Clearly, the aim is to choose z_k in (3.2)–(3.3) such that $r_k \approx 0$ as good as possible. In the BCG approach, this is attempted by enforcing the Galerkin condition (2.9). Using (2.3)–(2.4) and (3.3), we easily verify that (2.9) holds if and only if r_k and v_{k+1} are parallel or, equivalently, z_k is a solution of the linear system

$$T_k z = \beta_1 e_1. \tag{3.5}$$

Note that, by (3.1), (3.5) is inconsistent if T_k is singular. Thus we have the following result.

PROPOSITION 3.1. *A* BCG *iterate* x_k^{BCG} *satisfying the Galerkin condition* (2.9) *exists if and only if* T_k *is nonsingular. Moreover, if it exists, it is unique and given by*

$$x_k^{\mathrm{BCG}} = x_0 + V_k z_k \quad \text{and} \quad r_k = -\beta_{k+1}(z_k)_k v_{k+1} \tag{3.6}$$

where z_k *is the solution of* (3.5) *and* $(z_k)_k$ *denotes its* k*th component.*

Proposition 3.1 demonstrates the defects of the BCG approach. Simple examples show that singular T_k may indeed occur, and then, in view of Proposition 2.4, the BCG Algorithm 2.3 would break down in exact arithmetic. In floating-point arithmetic, such a breakdown is unlikely to happen. However, T_k may still be close to singular and then the Galerkin condition (2.9) defines a poor approximation to the true solution of (1.1). This is the reason for the typical erratic convergence behavior with wildly oscillating residual norms.

Obviously, the question arises as to whether there is a better strategy than (2.9) for choosing z_k in (3.2)–(3.3). Ideally, we would like to have the minimal residual (MR) property

$$\|b - Ax_k\| = \min_{x \in x_0 + K_k(r_0, A)} \|b - Ax\| = \min_{z \in \mathbb{C}^k} \|V_{k+1}\big(\beta_1 e_1 - \tilde{T}_k z_k\big)\|. \tag{3.7}$$

However, by (2.3), in general (see Theorem 3.4 for an exception) the columns of V_{k+1} are orthonormal only with respect to (2.6) rather than the Euclidean inner product $(x, y) = y^H x$. Consequently, solving the least-squares problem on the right-hand side of (3.7) results in an algorithm for which work and storage per iteration step k grows linearly with k. Hence, if we insist on a "true" iterative scheme with constant work and storage per iteration, this excludes the MR method.

Here, we propose the *quasi-minimal residual* (QMR) approach as a substitute for (3.7). Let

$$\Omega_{k+1} = \mathrm{diag}(\omega_1, \omega_2, \cdots, \omega_{k+1}) \quad \text{with} \quad \omega_j > 0 \quad \text{for all} \quad j$$

be a given positive diagonal weight matrix and rewrite (3.3) in the form

$$r_k = \big(V_{k+1}\Omega_{k+1}^{-1}\big)\big(\omega_1 \beta_1 e_1 - \Omega_{k+1}\tilde{T}_k z_k\big). \tag{3.8}$$

Instead of $\|r_k\|$ as in (3.7), we may at least minimize the vector of components in the representation (3.8) of r_k:

$$\min_{z\in\mathbb{C}^k} \|\omega_1\beta_1 e_1 - \Omega_{k+1}\tilde{T}_k z\|. \tag{3.9}$$

Hence, we define the iterates of the QMR method as follows:

$$x_k = x_k^{\mathrm{QMR}} = x_0 + V_k z_k \quad \text{where } z_k \in \mathbb{C}^k \text{ is the solution of (3.9).} \tag{3.10}$$

Notice that $\Omega_{k+1}\tilde{T}_k$ is a $(k+1)\times k$ matrix which, by (3.4) and (3.1), has full rank. Thus, the least squares problem (3.9) always has a unique solution z_k.

Clearly, the QMR approach still depends on the weights ω_j. A natural choice is

$$\omega_j = \|v_j\|, \quad j = 1, 2, \cdots, k+1, \tag{3.11}$$

so that all basis vectors v_j/ω_j in the representation (3.8) of r_k have Euclidean length 1. Our numerical tests (cf. §6) also confirmed (3.11) as the best strategy.

3.2. Practical implementation. Next we present an algorithm for the actual computation of the QMR iterates (3.10). The derivation is similar to that of Paige and Saunders' SYMMLQ and MINRES algorithms [36] for real symmetric matrices.

By (3.4), (2.1), and (3.1), $\Omega_{k+1}\tilde{T}_k$ is a tridiagonal $(k+1)\times k$ matrix with full column rank. Hence it admits a QR factorization of the type

$$Q_{k+1}\Omega_{k+1}\tilde{T}_k = \begin{bmatrix} R_k \\ 0 \end{bmatrix} \tag{3.12}$$

where Q_{k+1} is a unitary $(k+1)\times(k+1)$ matrix and R_k a nonsingular matrix of the form

$$R_k := \begin{bmatrix} \zeta_1 & \eta_2 & \theta_3 & 0 & \dots & 0 \\ 0 & \zeta_2 & \eta_3 & \ddots & \ddots & \vdots \\ 0 & \ddots & \zeta_3 & \ddots & \ddots & 0 \\ \vdots & & \ddots & \ddots & \ddots & \theta_k \\ \vdots & & & \ddots & \ddots & \eta_k \\ 0 & \dots & \dots & \dots & 0 & \zeta_k \end{bmatrix}. \tag{3.13}$$

The decomposition (3.12) can be generated by means of a series of k complex Givens rotations (e.g., [20, p. 47])

$$Q(c_j, s_j) = \begin{bmatrix} c_j & \overline{s}_j \\ -s_j & c_j \end{bmatrix}, \quad c_j \in \mathbb{R}, s_j \in \mathbb{C}, \quad c_j^2 + |s_j|^2 = 1, \quad j = 1, \cdots, k.$$

In particular, (3.12) is easily updated from the factorization $Q_k\Omega_k\tilde{T}_{k-1} = R_{k-1}$ of the previous step by setting

$$Q_{k+1} = \begin{bmatrix} I_{k-1} & 0 \\ 0 & Q(c_k, s_k) \end{bmatrix} \begin{bmatrix} Q_k & 0 \\ 0 & 1 \end{bmatrix} \tag{3.14}$$

and computing c_k, s_k and the new elements θ_k, η_k, ζ_k of R_k as follows:

$$\begin{aligned} &\theta_k = \overline{s_{k-2}}\omega_{k-1}\beta_k, \qquad \eta_k = c_{k-1}c_{k-2}\omega_{k-1}\beta_k + \overline{s_{k-1}}\omega_k\alpha_k, \\ &\tilde{\zeta}_k = c_{k-1}\omega_k\alpha_k - s_{k-1}c_{k-2}\omega_{k-1}\beta_k, \qquad |\zeta_k| = \left(|\tilde{\zeta}_k|^2 + \omega_{k+1}^2|\beta_{k+1}|^2\right)^{1/2}, \\ &\zeta_k = \begin{cases} |\zeta_k|\tilde{\zeta}_k/|\tilde{\zeta}_k|, & \text{if } \tilde{\zeta}_k \neq 0, \\ |\zeta_k|, & \text{if } \tilde{\zeta}_k = 0, \end{cases} \qquad c_k = \tilde{\zeta}_k/\zeta_k, \quad s_k = \omega_{k+1}\beta_{k+1}/\zeta_k. \end{aligned} \tag{3.15}$$

By (3.12) and since Q_{k+1} is unitary, (3.9) is equivalent to

$$\min_{z\in\mathbb{C}^k} \left\| \omega_1\beta_1 Q_{k+1}e_1 - \begin{bmatrix} R_k \\ 0 \end{bmatrix} z \right\|. \tag{3.16}$$

From (3.10) and (3.16) it follows that

$$x_k = x_0 + V_k z_k \quad \text{where} \quad z_k := R_k^{-1}t_k, \quad \begin{bmatrix} t_k \\ \tilde{\tau}_{k+1} \end{bmatrix} = \tilde{t}_{k+1} := \omega_1\beta_1 Q_{k+1}e_1. \tag{3.17}$$

Notice that, in view of (3.14), t_k differs from the previous vector t_{k-1} only by its kth component $\tau_k := (t_k)_k = c_k\tilde{\tau}_k$. Next, we define vectors p_j via

$$[p_1 \quad p_2 \quad \cdots \quad p_k] := V_k R_k^{-1}. \tag{3.18}$$

Finally, using (3.17)–(3.18) and (3.13), we obtain the recursion

$$x_k = x_{k-1} + \tau_k p_k, \quad \text{where} \quad p_k = \frac{1}{\zeta_k}\Big(v_k - \eta_k p_{k-1} - \theta_k p_{k-2}\Big),$$

for the QMR iterates. In combination with Algorithm 2.1, the following implementation results:

ALGORITHM 3.2 (QMR METHOD).

(1) *Start:*

- *Choose* $x_0 \in \mathbb{C}^n$;
- *Set* $\tilde{v}_1 = b - Ax_0$, $v_0 = p_0 = p_{-1} = 0$;
- *Set* $\beta_1 = \left(\tilde{v}_1^T\tilde{v}_1\right)^{1/2}$, $\tilde{\tau}_1 = \omega_1\beta_1$, $c_0 = c_{-1} = 1$, *and* $s_0 = s_{-1} = 0$.

(2) *For* $k = 1, 2, \cdots$ *do:*

- *If* $\beta_k = 0$, *stop:* x_{k-1} *solves* $Ax = b$.
- *Otherwise, compute* $v_k = \tilde{v}_k/\beta_k$ *and* $\alpha_k = v_k^T A v_k$;
- *Set* $\tilde{v}_{k+1} = Av_k - \alpha_k v_k - \beta_k v_{k-1}$, $\beta_{k+1} = \left(\tilde{v}_{k+1}^T\tilde{v}_{k+1}\right)^{1/2}$;
- *Compute* θ_k, η_k, ζ_k, c_k, *and* s_k, *using formulas* (3.15);
- *Set* $p_k = (v_k - \eta_k p_{k-1} - \theta_k p_{k-2})/\zeta_k$;
- *Set* $\tau_k = c_k\tilde{\tau}_k$, $\tilde{\tau}_{k+1} = -s_k\tilde{\tau}_k$;
- *Compute* $x_k = x_{k-1} + \tau_k p_k$.

The assumption (3.1) guarantees that, in exact arithmetic, Algorithm 3.2 stops for $k = m_\star + 1$ and, by (2.2), x_{k-1} is indeed the solution of (1.1) then. However, in floating-point arithmetic, this finite termination property of the Lanczos recursion is no longer valid, and the stopping criterion stated in Algorithm 3.2 is not useful in practice. Instead, we should terminate the iteration as soon as $\|r_k\|$ is sufficiently reduced. We remark that r_k is not directly available in Algorithm 3.2. However, in view of (3.19), if we update one additional auxiliary vector, namely,

$$h_k = h_{k-1} + \frac{c_k\tilde{\tau}_{k+1}}{|s_1 s_2 \cdots s_k|^2\omega_{k+1}} v_{k+1}, \quad h_0 := r_0,$$

then $\|r_k\|$ can be computed via

$$\|r_k\| = |s_1 s_2 \cdots s_k|^2 \cdot \|h_k\|.$$

Finally, notice that, for the weighting strategy (3.11),

$$\|v_k\| = \frac{\sqrt{f^T f + g^T g}}{|\beta_k|}, \quad f := \operatorname{Re}\tilde{v}_k, \; g := \operatorname{Im}\tilde{v}_k,$$

can be obtained without extra cost during the computation of $\tilde{v}_k^T \tilde{v}_k = f^T f - g^T g + 2if^T g$.

3.3. Properties. In this subsection, we list some further properties of the QMR approach.

PROPOSITION 3.3. *For* $k = 1, 2, \cdots, m_\star$:

(a)

$$r_k^{\mathrm{QMR}} = |s_k|^2 r_{k-1}^{\mathrm{QMR}} + (c_k \tilde{\tau}_{k+1}/\omega_{k+1}) v_{k+1}; \tag{3.19}$$

(b) *The* BCG *iterate* x_k^{BCG} *defined by* (2.9) *exists if and only if* $c_k \neq 0$. *Moreover, if* $c_k \neq 0$, *then*

$$x_k^{\mathrm{BCG}} = x_{k-1}^{\mathrm{QMR}} + (\tilde{\tau}_k/c_k) p_k, \tag{3.20}$$

$$\|r_k^{\mathrm{BCG}}\| = |\omega_1 \beta_1 s_1 s_2 \cdots s_{k-1} s_k| \cdot \|v_{k+1}\| / (\omega_{k+1} |c_k|). \tag{3.21}$$

Proof. (a) By (3.17), (3.12), and (3.8), we have

$$r_k^{\mathrm{QMR}} = \tilde{\tau}_{k+1} \tilde{w}_{k+1} \quad \text{where} \quad \tilde{w}_{k+1} := V_{k+1} \Omega_{k+1}^{-1} Q_{k+1}^H \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}. \tag{3.22}$$

With (3.14), it follows that successive vectors $\tilde{w}_{k+1}$ and $\tilde{w}_k$ are connected by

$$\tilde{w}_{k+1} = -\overline{s_k} \tilde{w}_k + (c_k/\omega_{k+1}) v_{k+1}. \tag{3.23}$$

Finally, by combining (3.23) and (3.22) and using $\tilde{\tau}_{k+1} = -s_k \tilde{\tau}_k$, we obtain (3.19).

(b) First we note that (3.12), (3.4), and (3.14) imply

$$Q_k \Omega_k T_k = \begin{bmatrix} I_{k-1} & 0 \\ 0 & c_k \end{bmatrix} R_k. \tag{3.24}$$

Thus, by Proposition 3.1, x_k^{BCG} exists if and only if $c_k \neq 0$. Now assume $c_k \neq 0$. Using (3.5)–(3.6), (3.24), and (3.17), we get

$$x_k^{\mathrm{BCG}} = x_0 + V_k z_k^{\mathrm{BCG}} \quad \text{where} \quad z_k^{\mathrm{BCG}} = R_k^{-1} \begin{bmatrix} t_{k-1} \\ \tilde{\tau}_k/c_k \end{bmatrix}. \tag{3.25}$$

By comparing (3.25) with (3.17), (3.20) follows. For the proof of (3.21), notice that, by (3.25), (3.13) , and the formula for s_k in (3.15),

$$\beta_{k+1} (z_k^{\mathrm{BCG}})_k = \beta_{k+1} \tilde{\tau}_k / (\zeta_k c_k) = \tilde{\tau}_k s_k / (\omega_{k+1} c_k). \tag{3.26}$$

Furthermore, Algorithm 3.2 shows that

$$|\tilde{\tau}_k| = |\omega_1 \beta_1 s_1 s_2 \cdots s_{k-1}|. \tag{3.27}$$

Finally, by inserting (3.26)–(3.27) into the formula (3.6) for r_k^{BCG}, we arrive at (3.21). □

In view of part (b) of Proposition 3.3, the QMR method has the additional feature that it also yields *all* existing BCG iterates. This is in contrast to the BCG Algorithm 2.3, which breaks down as soon as the *first* nonexisting BCG iterate is encountered. We remark that, by (3.21), $\|r_k^{\mathrm{BCG}}\|$ can be computed without extra cost from quantities which are generated in Algorithm 3.2 anyway. In particular, we may monitor $\|r_k^{\mathrm{BCG}}\|$ during the course of the QMR algorithm, and, whenever the actual BCG iterate is desired, compute x_k^{BCG} via (3.20).

There is an important special case for which the QMR method (with weighting strategy (3.11)) is even equivalent to the MR approach (3.7). Consider the subclass of (1.3) of complex symmetric matrices of the form

$$A = T + i\sigma I, \quad T = T^T \text{ real symmetric}, \quad \sigma > 0. \tag{3.28}$$

Assume that $r_0 \in \mathbb{R}^n$ (this can always be achieved by a proper choice of x_0). Then it is easily verified that the Lanczos vectors v_k generated by Algorithm 2.1 are all real and therefore, by (2.3), orthonormal with respect to the usual Euclidean inner product. In particular, by (3.11), $\omega_j \equiv 1$, and the least squares problem (3.9) is equivalent to the one on the right-hand side of (3.7). Hence we have the following result.

THEOREM 3.4. *Let A be of the form* (3.28) *and $r_0 \in \mathbb{R}^n$. Then, the iterates x_k generated by Algorithm* 3.2 (*with $\omega_j \equiv 1$*) *satisfy the minimal residual property* (3.7).

4. On the breakdown of the complex symmetric Lanczos algorithm. In the general nonsymmetric Lanczos process a breakdown—more precisely, division by 0—may occur, before an invariant subspace has been found (see, e.g., [43, p. 389]). Although this happens very rarely in practice, the possibility of such breakdowns has brought the nonsymmetric Lanczos method into discredit and has certainly kept many people from actually using the algorithm. On the other hand, it is possible to devise so-called *look-ahead* [42], [38], [27], [3] modifications of the Lanczos algorithm which allow it to skip—except in the very special case of an incurable breakdown [42], [37]—over those iterations in which the standard algorithm would break down. Note that this was already observed by Gragg [21, pp. 222–223] and, in the context of the partial realization problem, by Kung [30, Chap. IV] and Gragg and Lindquist [22]. However, a complete treatment of the modified Lanczos method and its intimate connection with orthogonal polynomials and Padé approximation was presented only recently by Gutknecht [23].

Like for the general nonsymmetric Lanczos process, the complex symmetric Algorithm 2.1 may break down, i.e., stop with $v^T v = 0$ and $v \neq 0$. Recall that, throughout §3, possible breakdowns of the complex symmetric Lanczos recursion were explicitly excluded by assuming (3.1). In this section we briefly sketch the basic idea of the look-ahead procedure for the special case of the complex symmetric Lanczos recursion and derive a new theoretical result concerning so-called incurable breakdowns for complex symmetric matrices.

Assume that a breakdown occurs in Algorithm 2.1. In view of Proposition 2.2, this happens if and only if there is no complete set of $m_\star$ Lanczos vectors $v_k \in K_k(r_0, A)$, $k = 1, \cdots, m_\star$, which are orthonormal (cf. (2.3)) with respect to the indefinite inner product (2.6). Clearly, there exists a maximal subset

$$\{k_1, k_2, \cdots, k_J\} \subsetneq \{1, 2, \cdots, m_\star\}, \quad 1 \leq k_1 < k_2 < \cdots < k_J \leq m_\star, \tag{4.1}$$

such that for each $j = 1, 2, \cdots, J$ there exists a vector $v_{k_j} \in K_{k_j}(r_0, A)$ satisfying the orthonormality relations

$$v_{k_j}^T v = 0 \quad \text{for all } v \in K_{k_j - 1}(r_0, A) \quad \text{and} \quad v_{k_j}^T v_{k_j} = 1. \tag{4.2}$$

By the definition of Krylov subspaces, $K_k(r_0, A) = \{P(A)r_0 \mid P \in \Pi_{k-1}\}$, and especially

$$v_{k_j} = P_{k_j - 1}(A) r_0 \quad \text{with} \quad P_{k_j - 1} \in \Pi_{k_j - 1}. \tag{4.3}$$

Therefore, we can rewrite (4.2) in terms of polynomials:

$$(P_{k_j - 1}, P) = 0 \quad \text{for all } P \in \Pi_{k_j - 2}, \quad (P_{k_j - 1}, P_{k_j - 1}) \neq 0, \tag{4.4}$$

with the indefinite inner product

$$(P,Q) := r_0^T P(A)Q(A)r_0. \tag{4.5}$$

A polynomial $P_{k_j-1} \in \Pi_{k_j-1}$ that fulfills (4.4) is called a regular orthogonal (with respect to (4.5)) polynomial of degree $k_j - 1$. It is well known [7], [23] that three successive regular orthogonal polynomials are connected via a three-term recurrence. By (4.3), it follows that there is a corresponding three-term recurrence relating the vectors v_{k_j-1}, v_{k_j}, and v_{k_j+1}. The look-ahead Lanczos procedure is a modification of Algorithm 2.1 which—based on this three-term relation—generates the vectors v_{k_j}, $j = 1, 2, \cdots, J$. These vectors can then be completed to a basis of K_{k_J} by setting, e.g.,

$$v_k = A^{k-k_j} v_{k_j} \quad \text{for} \quad k = k_j + 1, k_j + 2, \cdots, k_{j+1} - 1, \quad j = 0, 1, \cdots, J-1,$$

(cf. [19]). Here, for $j = 0$, we set $k_0 := 1$. We remark that the resulting look-ahead Lanczos algorithm produces block tridiagonal matrices T_{k_j}, $j = 1, \cdots, J$, of the type (2.1) with $(k_j - k_{j-1}) \times (k_j - k_{j-1})$ matrices α_{k_j} on the block diagonal.

In exact arithmetic, the outlined algorithm terminates with the block tridiagonal T_{k_J}. Suppose that $k_J = m_\star$ in (4.1). Then T_{k_J} represents the restriction of the matrix A to the A-invariant subspace $K_{m_\star}(r_0, A)$. Obviously, in view of (2.2), the solution of (1.1) can then be computed from the quantities generated by the look-ahead Lanczos procedure. On the other hand, if $k_J < m_\star$ in (4.1), it is not possible to obtain the solution of (1.1) by means of the Lanczos process. For this reason, the case $k_J < m_\star$ is called incurable breakdown.

Next, we derive a criterion for the occurrence of incurable breakdown in the complex symmetric Lanczos algorithm. In the following, it is assumed that A is diagonalizable. Then (e.g., [25, Thm. 3.4.13]), A has a complete set of orthonormal (with respect to (2.6)) eigenvectors. In particular, r_0 can be expanded into eigenvectors of A. More precisely, by collecting components corresponding to identical eigenvalues, we get

$$r_0 = \sum_{l=1}^{m_\star} \rho_l u_l \tag{4.6}$$

$$\text{where } \rho_l \neq 0, \quad Au_l = \lambda_l u_l, \quad \text{and, if } l \neq j, \quad \lambda_l \neq \lambda_j, \quad u_l^T u_j = 0.$$

Notice that, unless all eigenvalues of A are distinct, quasi-null vectors u_l may occur in (4.6). In view of the following theorem, this is equivalent to incurable breakdown.

THEOREM 4.1. *Let $A = A^T$ be a diagonalizable $n \times n$ matrix and $r_0 \in \mathbb{C}^n$. Then in (4.1), $k_J = m_\star$ if and only if the eigenvectors in the expansion (4.6) of r_0 satisfy*

$$u_l^T u_l \neq 0 \quad \textit{for all} \quad l = 1, \cdots, m_\star. \tag{4.7}$$

Proof. We need to show that (4.7) is equivalent to the existence of a regular orthogonal polynomial of degree $m_\star - 1$ with respect to the inner product (4.5). From the general theory of orthogonal polynomials, it is well known (e.g., [4, pp. 11–12]) that regular orthogonal polynomials of degree k exist if and only if the corresponding moment matrix $M_k := (\mu_{j+l})_{j,l=0,\cdots,k}$ is nonsingular. For the case of (4.5), by (4.6), we have

$$\mu_j := r_0^T A^j r_0 = \sum_{l=1}^{m_\star} \rho_l^2 \lambda_l^j u_l^T u_l, \quad j = 0, 1, \cdots. \tag{4.8}$$

Note that moment matrices are, in particular, Hankel matrices. By applying Kronecker's theorem on the rank of infinite Hankel matrices [18, pp. 204–207] to $M_\infty := (\mu_{j+l})_{j,l=0,1,\cdots}$, it follows that

$$\text{rank } M_\infty = \text{rank } M_k = \text{rank } M_{m-1} = m \quad \text{for all} \quad k \geq m-1, \tag{4.9}$$

where m is the number of poles of the rational function

$$f(z) := \sum_{j=0}^{\infty} \frac{\mu_j}{z^{j+1}}.$$

Using (4.8) and $\sum_{j=0}^{\infty} \lambda_l^j / z^{j+1} \equiv 1/(z-\lambda_l)$, we obtain the following expansion of f:

$$f(z) = \sum_{l=1}^{m_\star} \frac{\rho_l^2 u_l^T u_l}{z - \lambda_l} \quad \text{for all} \quad |z| > \max_{l=1,\cdots,m_\star} |\lambda_l|. \tag{4.10}$$

In particular, by (4.10), $m \leq m_\star$ with equality holding if and only if (4.7) holds true. Hence, in view of (4.9), $M_{m_\star - 1}$ is nonsingular if and only if (4.7) is fulfilled. This concludes the proof. □

As mentioned, (4.7) is guaranteed if A has only simple eigenvalues. Thus we have the following corollary.

COROLLARY 4.2. *If $A = A^T$ is an $n \times n$ matrix with n distinct eigenvalues, then incurable breakdowns cannot occur in the complex symmetric Lanczos Algorithm* 2.1.

5. Complex versus equivalent real linear systems. In this section, we study connections between (1.1) and its equivalent real versions. Unless stated otherwise, A is now assumed to be a general complex $n \times n$ matrix.

5.1. Equivalent real linear systems. By taking real and imaginary parts in (1.1), we can rewrite (1.1) as the real linear system

$$A_\star \begin{bmatrix} \text{Re } x \\ \text{Im } x \end{bmatrix} = \begin{bmatrix} \text{Re } b \\ \text{Im } b \end{bmatrix}, \quad A_\star := \begin{bmatrix} \text{Re } A & -\text{Im } A \\ \text{Im } A & \text{Re } A \end{bmatrix}. \tag{5.1}$$

A second real version of (1.1) is

$$A_{\star\star} \begin{bmatrix} \text{Re } x \\ -\text{Im } x \end{bmatrix} = \begin{bmatrix} \text{Re } b \\ \text{Im } b \end{bmatrix}, \quad A_{\star\star} := \begin{bmatrix} \text{Re } A & \text{Im } A \\ \text{Im } A & -\text{Re } A \end{bmatrix}. \tag{5.2}$$

Obviously, (5.1) and (5.2) are the only essentially different possibilities of rewriting (1.1) as a real $2n \times 2n$ system. Furthermore, note that $A_\star$ is nonsymmetric if and only if $A \neq A^H$ is non-Hermitian, whereas $A_{\star\star}$ is symmetric if and only if $A = A^T$. Hence, for complex symmetric linear systems the approach (5.2) appears to be especially attractive since it permits the use of simple CG-type methods such as SYMMLQ and MINRES [36] for real symmetric matrices.

In the following proposition, we collect some simple spectral properties of $A_\star$ and $A_{\star\star}$.

PROPOSITION 5.1. (a) *Let $J = X^{-1}AX$ be the Jordan normal form of A. Then $A_\star$ has the Jordan normal form*

$$\begin{bmatrix} J & 0 \\ 0 & \overline{J} \end{bmatrix} = X_\star^{-1} A_\star X_\star \quad \textit{where} \quad X_\star := \frac{1}{\sqrt{2}} \begin{bmatrix} X & -i\overline{X} \\ -iX & \overline{X} \end{bmatrix}. \tag{5.3}$$

In particular,

$$\sigma(A_\star) = \sigma(A) \cup \overline{\sigma(A)}. \tag{5.4}$$

(b) *The matrices $A_{\star\star}$ and $-A_{\star\star}$ are similar. In particular,*

$$-\lambda, \overline{\lambda}, -\overline{\lambda} \in \sigma(A_{\star\star}) \quad \textit{for all} \quad \lambda \in \sigma(A_{\star\star}). \tag{5.5}$$

Moreover,

$$\sigma(A_{\star\star}) = \{\lambda \in \mathbb{C} \mid \lambda^2 \in \sigma(\overline{A}A)\}.$$

(c) *Let $A = A^T$ be complex symmetric. Then, there exists a singular value decomposition (the so-called Takagi* SVD*) of A of the form*

$$A = U\Sigma U^T, \quad U \textit{ unitary}, \quad \Sigma = \operatorname{diag}(\sigma_1, \sigma_2, \cdots, \sigma_n) \geq 0. \tag{5.6}$$

Moreover, $A_{\star\star}$ is a real symmetric matrix with spectral decomposition

$$A_{\star\star} = \begin{bmatrix} Y & -Z \\ Z & Y \end{bmatrix} \begin{bmatrix} \Sigma & 0 \\ 0 & -\Sigma \end{bmatrix} \begin{bmatrix} Y & -Z \\ Z & Y \end{bmatrix}^T \quad \textit{where} \quad Y = \operatorname{Re} U, \ Z = \operatorname{Im} U. \tag{5.7}$$

Proof. (a) First, note that

$$X_\star = S \begin{bmatrix} X & 0 \\ 0 & \overline{X} \end{bmatrix} \quad \text{where} \quad S := \frac{1}{\sqrt{2}} \begin{bmatrix} I_n & -iI_n \\ -iI_n & I_n \end{bmatrix} \quad \text{is unitary.} \tag{5.8}$$

In particular, (5.8) shows that with X also $X_\star$ is nonsingular. We readily verify that

$$S^H A_\star S = \begin{bmatrix} A & 0 \\ 0 & \overline{A} \end{bmatrix},$$

and, in view of (5.8), this implies (5.3). Equation (5.4) is an obvious consequence of (5.3).

(b) Since

$$\begin{bmatrix} 0 & I_n \\ -I_n & 0 \end{bmatrix}^{-1} A_{\star\star} \begin{bmatrix} 0 & I_n \\ -I_n & 0 \end{bmatrix} = -A_{\star\star},$$

the real matrices $A_{\star\star}$ and $-A_{\star\star}$ are similar. Hence, (5.5) holds true. The relation between $\sigma(A_{\star\star})$ and $\sigma(\overline{A}A)$ is known (see [25, p. 214] for a proof).

(c) Equation (5.6) is the well-known Takagi singular value decomposition for symmetric matrices (e.g., [25, Cor. 3.4.4]). By rewriting (5.6) in terms of the real and imaginary parts of A and U, we obtain (5.7) (cf. [25, pp. 212–213]). □

Roughly speaking, Krylov subspace methods are most effective for coefficient matrices A whose spectrum, except for possibly a few isolated eigenvalues, is contained in a half-plane which excludes the origin of the complex plane. On the other hand, if this half-plane condition is not satisfied and if a large number of eigenvalues of A straddle the origin, usually the convergence of CG-type algorithms is prohibitively slow. Typically, in these situations (see [8], [13], [14] for examples), iterations based on Krylov subspaces generated by A offer no advantage over solving the normal equations (1.5) by standard CG. See Theorem 5.4 for a theoretical result along these lines.

For complex linear systems that arise in practice the half-plane condition is usually satisfied. Indeed, mostly

$$\sigma(A) \subset \{\lambda \in \mathbb{C} \mid \operatorname{Im} \lambda \geq 0\}. \tag{5.9}$$

However, by rewriting (1.1) as real linear systems (5.1), respectively, (5.2), we deliberately create coefficient matrices whose spectra are most unfavorable for Krylov subspace methods. The case (5.2) is especially bad since, in view of (5.5), $\sigma(A_{\star\star})$ is symmetric with respect to real and imaginary axis and hence the eigenvalues always embrace the origin. Similarly, by (5.4), the coefficient matrix $A_\star$ of (5.1) in general has eigenvalues in the upper as well as in the lower half-plane. In particular, if (5.9)

holds and, as in most applications, the Hermitian part $(A + A^H)/2$ of A is indefinite, the spectrum of $A_\star$ straddles the origin and the half-plane condition is not satisfied for $A_\star$. The following example illustrates this behavior.

Example 5.2. Consider the class (3.28) of complex symmetric matrices $A = T + i\sigma I$, where $T = T^T$ is real and $\sigma > 0$. Obviously,

$$\begin{aligned} \sigma(A) &= \{\lambda = \mu + i\sigma \mid \mu \in \sigma(T)\} \\ &\subset S := [\mu_m + i\sigma, \mu_M + i\sigma]. \end{aligned} \tag{5.10}$$

Here μ_m and μ_M denote the smallest and largest eigenvalue of T, respectively. Note that the complex line segment S is parallel to the real axis and always contained in the upper half of the complex plane. In view of (5.4), (5.10) implies

$$\sigma(A_\star) = \{\lambda = \mu \pm i\sigma \mid \mu \in \sigma(T)\} \subset S \cup \overline{S}.$$

We remark that $S \cup \overline{S}$ is a tandem slit consisting of the two complex intervals S and $\overline{S}$, which are parallel and symmetric to each other with respect to the real axis. Moreover, the eigenvalues of $A_\star$ straddle the origin if the Hermitian part T of A is indefinite. Finally, using (3.28) and part (b) of Proposition 5.1, we obtain

$$\begin{aligned} \sigma(A_{\star\star}) &= \{\lambda = \pm\sqrt{\mu^2 + \sigma^2} \mid \mu \in \sigma(T)\} \\ &\subset \left[-\sqrt{\mu_M^2 + \sigma^2}, -\sigma\right] \cup \left[\sigma, \sqrt{\mu_M^2 + \sigma^2}\right]. \end{aligned}$$

Note that the class (3.28) is closely related to shifted skewsymmetric matrices. Indeed, if, instead of $Ax = b$, we rewrite $-iAx = -ib$ as a real system (5.1), we obtain

$$(-iA)_\star = \begin{bmatrix} \sigma I_n & T \\ -T & \sigma I_n \end{bmatrix} = \sigma I_{2n} - N, \quad N := \begin{bmatrix} 0 & -T \\ T & 0 \end{bmatrix} \quad \left(= -N^T\right). \tag{5.11}$$

Then the eigenvalues are contained in a line segment which is parallel to the imaginary axis and symmetric with respect to the real axis:

$$\sigma\left((-iA)_\star\right) = \{\lambda = \sigma \pm i\mu \mid \mu \in \sigma(T)\} \subset [\sigma - i\rho, \sigma + i\rho], \quad \rho = \max\{|\mu_m|, |\mu_M|\}.$$

5.2. Correspondence of Krylov subspace methods. In analogy to (1.6) for complex linear systems (1.1), a Krylov subspace method for the solution of the equivalent real systems (5.1), respectively, (5.2) generates iterates

$$\begin{bmatrix} \operatorname{Re} x_k \\ \operatorname{Im} x_k \end{bmatrix} = \begin{bmatrix} \operatorname{Re} x_0 \\ \operatorname{Im} x_0 \end{bmatrix} + P(A_\star) \begin{bmatrix} \operatorname{Re} r_0 \\ \operatorname{Im} r_0 \end{bmatrix}, \qquad P \in \Pi_{k-1}^{(r)}, \tag{5.12}$$

respectively,

$$\begin{bmatrix} \operatorname{Re} x_k \\ -\operatorname{Im} x_k \end{bmatrix} = \begin{bmatrix} \operatorname{Re} x_0 \\ -\operatorname{Im} x_0 \end{bmatrix} + P(A_{\star\star}) \begin{bmatrix} \operatorname{Re} r_0 \\ \operatorname{Im} r_0 \end{bmatrix}, \qquad P \in \Pi_{k-1}^{(r)}. \tag{5.13}$$

Here and in the sequel, $\Pi_{k-1}^{(r)}$ denotes the subset of Π_{k-1} of polynomials with real coefficients. Furthermore, the notation

$$K_k^{(r)}(c, B) := \{P(B)c \mid P \in \Pi_{k-1}^{(r)}\} \quad \left(\subset K_k(c, B)\right)$$

will be used.

At first glance it might appear that Krylov subspace iterations (1.6), respectively, (5.12)–(5.13) for the original complex systems, respectively, its equivalent real versions correspond to each other. However, as the following proposition shows, this is not the case in general.

PROPOSITION 5.3. *Let* $k \in \mathbb{N}$.

(a) *Let* $P \in \Pi_{k-1}$. *Then,* $x_k = x_0 + P(A)r_0$ *is equivalent to*

$$\begin{bmatrix} \operatorname{Re} x_k \\ \operatorname{Im} x_k \end{bmatrix} = \begin{bmatrix} \operatorname{Re} x_0 \\ \operatorname{Im} x_0 \end{bmatrix} + P_1(A_\star) \begin{bmatrix} \operatorname{Re} r_0 \\ \operatorname{Im} r_0 \end{bmatrix} + P_2(A_\star) \begin{bmatrix} \operatorname{Im} r_0 \\ -\operatorname{Re} r_0 \end{bmatrix} \tag{5.14}$$

where $P = P_1 + iP_2$, $P_1, P_2 \in \Pi_{k-1}^{(r)}$.

(b) *Let* $P \in \Pi_{k-1}^{(r)}$. *Then,* (5.13) *is equivalent to*

$$x_k = \operatorname{Re} x_k + i \operatorname{Im} x_k = x_0 + R(\overline{A}A)\overline{r_0} + S(\overline{A}A)\overline{A}r_0 \tag{5.15}$$

where $R \in \Pi_{\lfloor (k-1)/2 \rfloor}^{(r)}$ *and* $S \in \Pi_{\lfloor (k-2)/2 \rfloor}^{(r)}$ *are defined by* $P(\lambda) \equiv R(\lambda^2) + \lambda S(\lambda^2)$.

Proof. First we note that, for $j = 0, 1, \cdots$,

$$(A_\star)^j = \begin{bmatrix} \operatorname{Re} A^j & -\operatorname{Im} A^j \\ \operatorname{Im} A^j & \operatorname{Re} A^j \end{bmatrix} \quad \text{and} \quad (A_{\star\star})^{2j} = \begin{bmatrix} \operatorname{Re}(\overline{A}A)^j & \operatorname{Im}(\overline{A}A)^j \\ -\operatorname{Im}(\overline{A}A)^j & \operatorname{Re}(\overline{A}A)^j \end{bmatrix}, \tag{5.16}$$

as is easily verified by induction on j.

(a) Let γ_j and δ_j be the coefficients of the real polynomials P_1 and P_2, respectively. Then

$$\begin{aligned} \operatorname{Re} P(A) &= \sum_{j=0}^{k-1} \bigl(\gamma_j \operatorname{Re} A^j - \delta_j \operatorname{Im} A^j\bigr), \\ \operatorname{Im} P(A) &= \sum_{j=0}^{k-1} \bigl(\gamma_j \operatorname{Im} A^j + \delta_j \operatorname{Re} A^j\bigr). \end{aligned} \tag{5.17}$$

By reformulating $x_k = x_0 + P(A)r_0$, by means of (5.17) and the first relation in (5.16), in terms of real and imaginary parts, we immediately obtain (5.14).

(b) A routine calculation, using the second identity in (5.16), shows that (5.13) can be rewritten as

$$\begin{bmatrix} \operatorname{Re} x_k \\ -\operatorname{Im} x_k \end{bmatrix} = \begin{bmatrix} \operatorname{Re} x_0 \\ -\operatorname{Im} x_0 \end{bmatrix} + \begin{bmatrix} \operatorname{Re}\{R(\overline{A}A)\overline{r}_0 + S(\overline{A}A)\overline{A}r_0\} \\ -\operatorname{Im}\{R(\overline{A}A)\overline{r}_0 + S(\overline{A}A)\overline{A}r_0\} \end{bmatrix}.$$

Hence (5.13) and (5.15) are equivalent. □

In view of part (a) of Proposition 5.3, the corresponding real equivalent of complex Krylov schemes (1.6) are iterations of the type (5.14) and not the obvious real Krylov subspace methods (5.12). Clearly, the actual choice of the polynomials in (1.6), respectively, (5.12)–(5.13) is aimed at obtaining iterates which are—in a certain sense—best possible approximations to the exact solution of the corresponding linear system. By using schemes of the type (5.12), from the first, we give up k of the $2k$ real parameters which are available for optimizing complex Krylov subspace methods (1.6). Consequently, it is always preferable to solve the complex system (1.1) rather than the real version (5.1) by Krylov subspace methods. Furthermore, numerical tests reveal that the convergence behavior of the two approaches can be drastically different (see § 6).

5.3. A connection between MR and CGNR for complex symmetric matrices. Now assume that A is a complex symmetric $n \times n$ matrix. Then, in view of part (c) of Proposition 5.1, $A_{\star\star}$ is a real symmetric indefinite matrix whose spectrum is given by

$$\sigma(A_{\star\star}) = \{\pm\sigma_j \mid j = 1, \cdots, n\}. \tag{5.18}$$

Here $\sigma_j = \sigma_j(A) \geq 0$, $j = 1, \cdots, n$, denote the singular values of A.

Since there are simple extensions [36] of classical CG to real symmetric indefinite matrices, it is especially tempting to solve (5.2) by one of these methods. The iterates of these algorithms are defined either via a Galerkin condition or a minimal residual (MR) property. Here we consider the MR approach. Applied to (5.2) it generates a sequence of iterates z_k, $k = 1, 2, \cdots$, which are characterized by

$$\|b_{\star\star} - A_{\star\star} z_k\| = \min_{z \in z_0 + K_k^{(r)}(r_0^{\star\star}, A_{\star\star})} \|b_{\star\star} - A_{\star\star} z\|, \quad z_k \in z_0 + K_k^{(r)}(r_0^{\star\star}, A_{\star\star}). \tag{5.19}$$

Here we have set

$$b_{\star\star} := \begin{bmatrix} \operatorname{Re} b \\ \operatorname{Im} b \end{bmatrix}, \quad z_k := \begin{bmatrix} \operatorname{Re} x_k \\ -\operatorname{Im} x_k \end{bmatrix} \text{ for } k = 0, 1, \cdots, \quad r_0^{\star\star} := b_{\star\star} - A_{\star\star} z_0. \tag{5.20}$$

Roughly speaking, CG-type algorithms for real symmetric indefinite systems converge slowly if the coefficient matrix is strongly indefinite in the sense that it has many positive as well as many negative eigenvalues. Unfortunately, since by (5.18), $\sigma(A_{\star\star})$ is even symmetric to the origin, $A_{\star\star}$ exhibits this undesirable property. Indeed, numerical tests show that the convergence behavior of the MR method (5.19) is practically identical to that of the tabooed approach to (1.1) via solving the normal equations (1.5) by standard CG [24]. In the sequel, we refer to this latter method as CGNR. Notice that the iterates x_k of CGNR are defined by the minimization property

$$\|b - Ax_l\| = \min_{x \in x_0 + K_l(A^H r_0, A^H A)} \|b - Ax\|, \quad x_l \in x_0 + K_l(A^H r_0, A^H A). \tag{5.21}$$

Next we prove that MR and CGNR are even equivalent if the starting residual $r_0^{\star\star}$ satisfies a certain symmetry condition. Note that, corresponding to the spectral decomposition (5.7), $r_0^{\star\star}$ can be expanded into eigenvectors of $A_{\star\star}$ as follows:

$$r_0^{\star\star} = \begin{bmatrix} Y & -Z \\ Z & Y \end{bmatrix} c \quad \text{with} \quad c = \begin{bmatrix} c_1 \\ \vdots \\ c_{2n} \end{bmatrix} \in \mathbb{R}^{2n}. \tag{5.22}$$

THEOREM 5.4. *Let x_k^{MR}, respectively, x_l^{CGNR} denote the iterates generated by (5.19)–(5.20), respectively, (5.21) starting with the same initial guess $x_0 \in \mathbb{C}^n$. Assume that c in the expansion (5.22) of $r_0^{\star\star}$ satisfies*

$$|c_j| = |c_{n+j}|, \qquad j = 1, 2, \cdots, n. \tag{5.23}$$

Then,

$$x_l^{\mathrm{CGNR}} = x_{2l}^{MR} = x_{2l+1}^{\mathrm{MR}}, \qquad l = 0, 1, \cdots. \tag{5.24}$$

Proof. First note that, in view of (5.7) and (5.22), c_j and c_{n+j} are components corresponding to a pair of symmetric eigenvalues $\pm\sigma_j$ of $A_{\star\star}$. However, for any real symmetric linear system $A_{\star\star} z = b_{\star\star}$ with "symmetric" eigenvalues and "symmetric" starting residual $r_0^{\star\star}$ in the sense of (5.18) and (5.23), respectively, the MR method generates iterates with $z_k \in z_0 + K_{\lfloor k/2 \rfloor}^{(r)}(A_{\star\star} r_0^{\star\star}, A_{\star\star}^2)$ (see, e.g., [14]). Consequently the iterates defined by (5.19) satisfy

$$z_{2l} = z_{2l+1} \in z_0 + K_l^{(r)}(A_{\star\star} r_0^{\star\star}, A_{\star\star}^2). \tag{5.25}$$

In particular, by (5.20), (5.25) shows that $x_{2l}^{\mathrm{MR}} = x_{2l+1}^{\mathrm{MR}}$.

It remains to prove the first relation in (5.24). To this end, we remark that

$$\|b_{\star\star} - A_{\star\star} z\| = \|b - Ax\| \quad \text{for all} \quad z = \begin{bmatrix} \operatorname{Re} x \\ -\operatorname{Im} x \end{bmatrix}, \quad x \in \mathbb{C}^n. \tag{5.26}$$

Moreover, by using (5.20) and part (b) of Proposition 5.3 (applied to polynomials $P(\lambda) \equiv \lambda S(\lambda^2)$), we deduce

$$z_0 + K_l^{(r)}(A_{\star\star} r_0^{\star\star}, (A_{\star\star})^2) = \left\{ \begin{bmatrix} \operatorname{Re} x \\ -\operatorname{Im} x \end{bmatrix} \;\middle|\; x \in x_0 + K_l^{(r)}(A^H r_0, A^H A) \right\} \tag{5.27}$$

(notice that $\overline{A} = A^H$ in (5.15)!). In view of (5.25)–(5.27), (5.19) (for $k = 2l$) can be rewritten in the form

$$\|b - Ax_{2l}^{MR}\| = \min_{x \in x_0 + K_l^{(r)}(A^H r_0, A^H A)} \|b - Ax\|, \quad x_{2l}^{\mathrm{MR}} \in x_0 + K_l^{(r)}(A^H r_0, A^H A). \tag{5.28}$$

Finally, note that the iterates of CGNR always correspond to real polynomials, i.e., $x_l^{\mathrm{CGNR}} \in x_0 + K_l^{(r)}(A^H r_0, A^H A)$. Hence, by comparing (5.21) with (5.28), we conclude that $x_l^{\mathrm{CGNR}} = x_{2l}^{\mathrm{MR}}$. □

Clearly, the special symmetry condition (5.23) will not be satisfied in general. Nevertheless, all our numerical experiments showed (cf. § 6) that (5.24) is still fulfilled approximately, i.e.,

$$x_l^{\mathrm{CGNR}} \approx x_{2l}^{\mathrm{MR}} \approx x_{2l+1}^{\mathrm{MR}}, \qquad l = 0, 1, \cdots . \tag{5.29}$$

6. Numerical examples. We have performed numerical experiments with all algorithms considered in this paper in numerous cases. In this section, we present a few typical results of these experiments.

Consider (1.2) on the unit square $G := (0,1) \times (0,1)$ with $\sigma_1 \in \mathbb{R}$ a constant and σ_2 a real coefficient function. First assume that u satisfies Dirichlet boundary conditions. Then, approximating (1.2) by finite differences on a uniform $m \times m$ grid with mesh size $h := 1/(m+1)$ yields a linear system (1.1) with A an $n \times n$, $n := m^2$, matrix of the form

$$A = T + ih^2 D, \quad T := A_0 - \sigma_1 h^2 I, \quad D = \operatorname{diag}(d_1, d_2, \cdots, d_n). \tag{6.1}$$

Here A_0 is the symmetric positive definite matrix arising from the usual five-point discretization of $-\Delta$ and the diagonal elements of D are just the values of σ_2 at the grid points.

Similarly, if we consider the real Helmholtz equation (1.2), i.e., $\sigma_2 \equiv 0$, but now with a typical complex boundary condition such as

$$\frac{\partial u}{\partial n} = i\alpha u \quad \text{on} \quad \{(1, y) \mid -1 < y < 1\}$$

(which is discretized using forward differences) and Dirichlet boundary conditions on the other three sides of the boundary of G, we again arrive at (6.1), where

$$d_j = \begin{cases} \alpha/h, & \text{if } j = lm,\ l = 1, \cdots, m, \\ 0, & \text{otherwise.} \end{cases} \tag{6.2}$$

The test problems presented in this section are all linear systems $Ax = b$ with complex symmetric coefficient matrices of the type (6.1). For Example 6.1, the mesh size $h = 1/64$ was chosen resulting in a 3969×3969 matrix A. In Examples 6.2–6.4, $h = 1/32$ and thus A is a 961×961 matrix. The right-hand side b was chosen to be a

vector with random components in $[-1,1]+i[-1,1]$, with the exception of Example 6.2 where b had constant components $1+i$. As starting vector, $x_0 = 0$ was chosen.

As stopping criterion, we used

$$R_k := \frac{\|b - Ax_k\|}{\|b - Ax_0\|} \leq 10^{-6}. \tag{6.3}$$

In Figs. 6.1–6.4, the relative residual norm (6.3), R_k, is plotted versus the number N_k of matrix-vector products with A, $A_\star$, or $A_{\star\star}$. Note that $N_k = k$ is identical to the iteration number, except for CGS, respectively, CGNR, which both require two matrix-vector products $A \cdot v$, respectively, $A \cdot v$, $\overline{A} \cdot v$ per iteration and for which $N_k = 2k$. For GMRES [40], work and storage per iteration step k grows linearly with k and in practice it is necessary to use restarts. In the sequel, GMRES(k_0) and GMRES$_\star$(k_0) refer to complex and real versions—restarted after every k_0 iterations—of the GMRES method applied to (1.1) and (5.1), respectively.

In a first series of experiments, QMR (with different weighting strategies) and BCG were compared. The natural choice (3.11) turned out to be the best strategy in all cases. In the following, QMR always refers to Algorithm 3.2 with weights (3.11). Then QMR produces residual vectors whose norms are almost monotonically decreasing and generally smaller than those of the BCG residuals. However, convergence of QMR and BCG typically occurred after a comparable number of iterations. The following example is typical.

Example 6.1. Here (6.1) is a 3969×3969 matrix with $\sigma_1 = 200$, and the diagonal elements of D are given by (6.2) with $\alpha = 10$. In Fig. 6.1, the convergence behavior of BCG, QMR, and of the unweighted version ($\omega_j \equiv 1$) of the QMR Algorithm 3.2 is displayed.

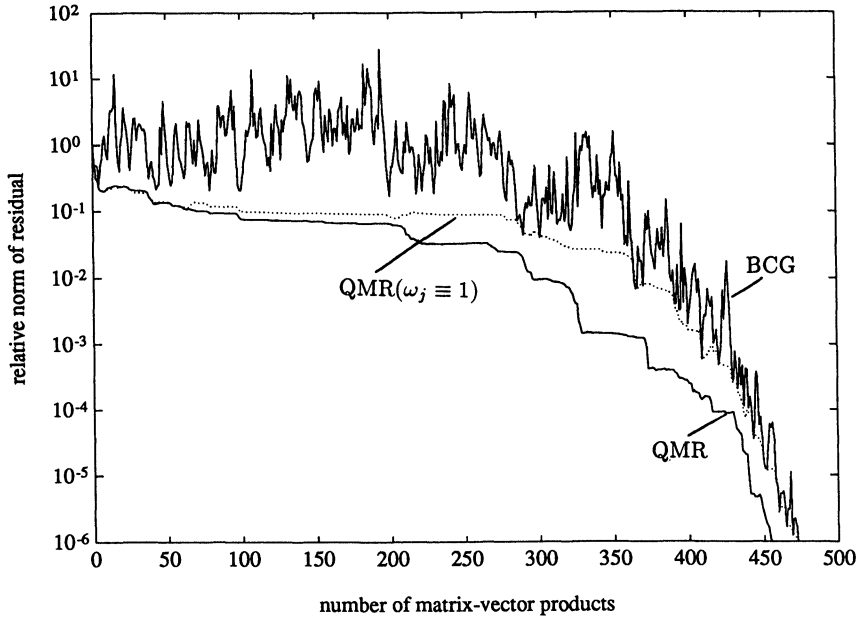

FIG. 6.1

Next we compared the CGS Algorithm 2.5 and complex GMRES with QMR and BCG. Typically, CGS needed slightly fewer iterations than QMR and BCG to

reach (6.3). However, per iteration, QMR and BCG require only about half as much work and storage and thus CGS is more expensive than QMR or BCG for complex symmetric matrices. Due to the necessary restarts, GMRES was never competitive with QMR, BCG, or CGS.

Example 6.2. In (6.1) we set $n = 961$, $\sigma_1 = 100$, and d_j; $j = 1, \cdots, n$, are chosen as random numbers in $[0, 10]$. Figure 6.2 shows the convergence behavior of GMRES(20), QMR, BCG, and two runs of CGS with different starting vectors s_0, namely, $s_0 = r_0$, respectively, s_0 with random components in $[-1, 1] + i[-1, 1]$. Notice the extremely large residual norms in the early stage of the CGS iteration.

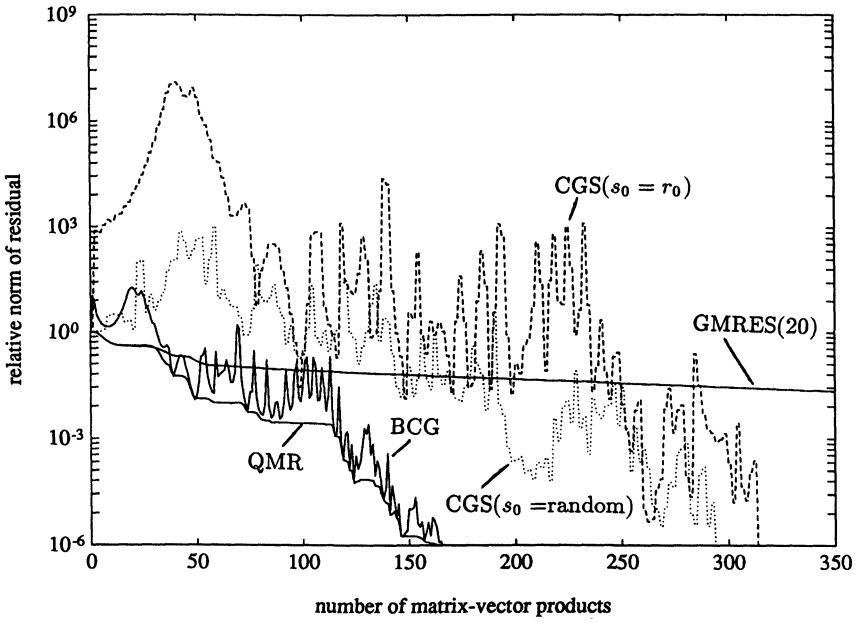

FIG. 6.2

In the following two examples we compared CG-type methods for $Ax = b$ with real schemes for the equivalent real systems (5.1), respectively, (5.2).

MR($A_{\star\star}$) denotes the minimal residual method (5.19) applied to the real symmetric system (5.2).

Example 6.3. Here, in (6.1), $n = 961$, $\sigma_1 = 100$, and d_j are given by (6.2) with $\alpha = 100$. In Fig. 6.3, the convergence behavior of QMR, MR($A_{\star\star}$), GMRES(20), GMRES(5), GMRES$_\star$(5), and CGNR is shown. Notice that, although the symmetry condition (5.23) is not fulfilled, the curves for CGNR and MR($A_{\star\star}$) are almost identical. This confirms (5.29). Finally, we tried GMRES(k_0) and GMRES$_\star$(k_0) also with other restart parameters k_0. For this example, both methods never did converge.

Example 6.4. Let A be the 961×961 matrix (6.1) with $\sigma_1 = 1000$, $D = \sigma_2 I$, $\sigma_2 = 100$, and set $\sigma := \sigma_2 h^2$. Note that A is a shifted Hermitian matrix of the form (3.28) (cf. Example 5.2). In particular, A belongs to the class of matrices (1.3) for which efficient true minimal residual algorithms for solving $Ax = b$ exist. Here we used the particular implementation, MR(A), derived in [16, Algorithm 2]. Recall that, by rewriting $-iAx = -ib$ as a real system (5.1), we obtain a shifted skewsymmetric matrix (5.11), $(-iA)_\star$. Again, for such matrices an efficient true minimal residual algorithm, denoted by MR($(-iA)_\star$), exists [9], [13]. Figure 6.4 shows the convergence

behavior of MR(A), MR($A_{\star\star}$), MR($(-iA)_\star$),CGNR, and GMRES(20). Notice that MR($(-iA)_\star$) and CGNR are nearly identical. This is typical for the case in which σ is small compared to the spectral radius of T. Furthermore, if $\sigma = 0$, i.e., $(-iA)_\star$ in (5.11) is skewsymmetric, CGNR and MR($(-iA)_\star$) are even equivalent [13].

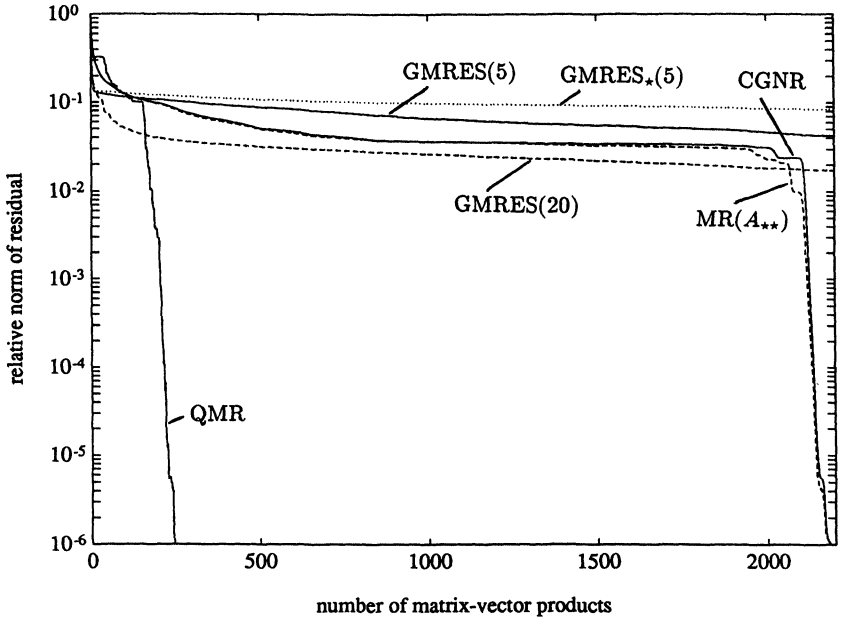

FIG. 6.3

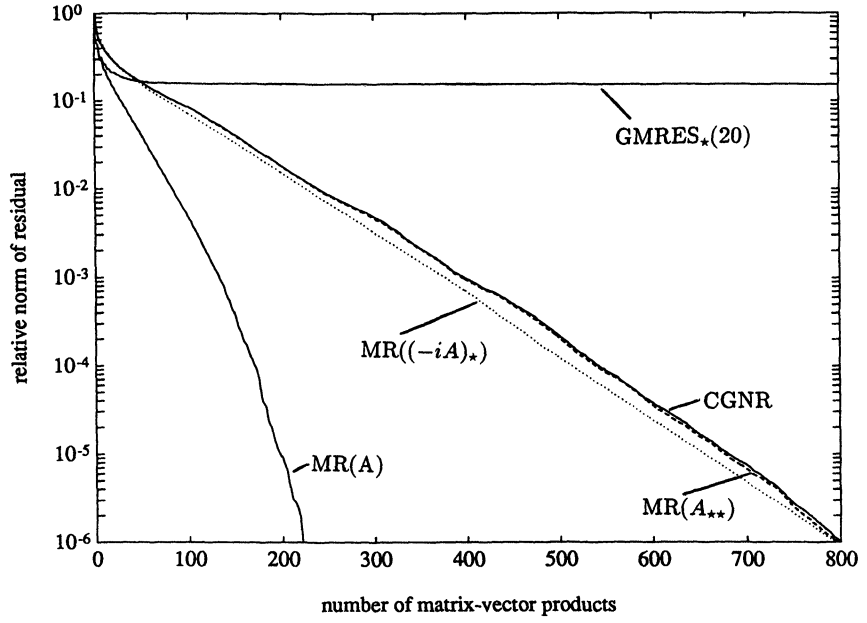

FIG. 6.4

7. Concluding remarks. Complex linear systems $Ax = b$, which arise in practice, often have complex symmetric coefficient matrices A. In this paper we have explored the use of a variant of the nonsymmetric Lanczos process for complex symmetric matrices for the solution of such linear systems. In particular, we have proposed a new method of defining approximate solutions of $Ax = b$ via a quasi-minimal residual (QMR) property. In contrast to the biconjugate gradient (BCG) approach, the QMR iterates are well defined as long as the basic Lanczos recursion does not break down. Moreover, unlike the wildly oscillating BCG residuals, the QMR residuals converge almost monotonically. Also, existing BCG iterates can be easily computed from the quantities generated during the QMR iteration. Finally, possible breakdowns—except incurable ones—of the complex symmetric Lanczos recursion can be overcome by using a look-ahead version of the Lanczos process. Incurable breakdowns occur only in very special situations. For example, they cannot occur if all eigenvalues of A are distinct.

It is very tempting (and often done in practice!) to avoid complex linear systems by solving equivalent real systems instead. We have presented some theoretical and numerical results which show that this—at least for Krylov subspace methods—is a fatal approach. Typically, the resulting real systems are unequally harder to solve by conjugate gradient-type algorithms than the original complex ones.

In this paper we have not addressed the question of how to choose preconditioners M for complex symmetric linear systems. This will be the subject of a forthcoming report. Here, we remark only that complex symmetry is preserved under preconditioning as long as M is complex symmetric. In particular, all algorithms for $A = A^T$ that we have considered can be used in conjunction with a complex symmetric preconditioner M. Note that the standard techniques, such as incomplete factorization [34], applied to $A = A^T$ generate complex symmetric preconditioners M.

Finally, we would like to mention that the quasi-minimal residual approach can also be used to stabilize the general nonsymmetric biconjugate gradient algorithm [17].

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