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NONNEGATIVE AND SKEW-SYMMETRIC PERTURBATIONS OF A MATRIX WITH POSITIVE INVERSE

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ABSTRACT. Let A be a nonsingular matrix with positive inverse and B a nonnegative matrix. Let the inverse of $A + vB$ be positive for $0 \le v < v^* < +\infty$ and at least one of its entries be equal to zero for $v = v^*$; an algorithm to compute v^* is described in this paper. Furthermore, it is shown that if $A + A^{\mathrm{T}}$ is positive definite, then the inverse of $A + v(B - B^{\mathrm{T}})$ is positive for $0 \le v < v^*$.

1. INTRODUCTION

Let

$$A + vB \tag{1}$$

be an $n \times n$ real matrix, where A is a nonsingular matrix with positive inverse ([5, 2, 1]), B $(B \neq 0)$ a nonnegative matrix and v a nonnegative real parameter,

$$A^{-1} > 0, \quad B \ge 0, \quad B \neq 0, \quad v \ge 0. \tag{2}$$

The parameter v may be considered as a measure of the size of the nonnegative perturbation vB of the matrix A. Let

$$Z(v) = (A + vB)^{-1} = [z_{ij}(v)]. \tag{3}$$

For $v = 0$, we have $Z(0) = A^{-1} > 0$; thus, $\det(A + vB) \neq 0$ and $Z(v) > 0$ in a sufficiently small neighborhood of 0. This paper addresses the problem of finding the largest, possibly infinite, number v^* such that $A + vB$ is nonsingular and $Z(v) > 0$ in $[0, v^*)$. We will describe an algorithm (the iterative process (6)) to compute v^* if $v^* < +\infty$. In the case $v^* = +\infty$, the successive approximations defined by (6) form a sequence diverging monotonically to $+\infty$.

We shall consider also matrices of the type

$$C(v) = A + v(B - B^{\mathrm{T}}); \tag{4}$$

here the matrix A is perturbed by a skew-symmetric matrix which may be written as $B - B^{\mathrm{T}}$ with $B \ge 0$. It will be shown that if $A + A^{\mathrm{T}}$ is positive definite, then $C^{-1}(v) \ge Z(v) > 0$ in $[0, v^*)$, where Z is defined by (3).

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Numerical calculations have been performed by using the matrix involved in the discrete analog of the integro-differential equation

$$(5)\qquad \frac{\partial u}{\partial t} = \frac{\partial}{\partial x}\left[p\frac{\partial u}{\partial x}\right] + q[u_0 - u] + v\int_0^1 K(x, x')[u_0(x') - u(x')]\,dx'$$

with boundary conditions $u(0) = u(1) = 0$, where $p(x) > 0$, $q(x) \geq 0$, $u_0(x) \geq 0$, and $K(x, x') \geq 0$. Equation (5) is a model for a spatially distributed community whose migration has both a random and a special deterministic component; more complicated models (n-species communities, nonlinear) can be obtained including birth-death processes, competition and predator-prey interactions [4]. A direct finite difference approach to (5) provides a discrete approximation $\mathbf{u}$ of the steady state solution u satisfying an equation of the type $(A + vB)\mathbf{u} = \mathbf{f} \geq 0$, where $A + vB$ is of type (2); the positivity of its inverse assures the positivity and the stability of $\mathbf{u}$.

2. The inverse of $A + vB$

Lemma 1. *Assume* (2) *and let* $\det(A + vB) \neq 0$ *and* $Z(v) > 0$, *with* $Z(v)$ *as defined in* (3). *Then* $Z'(v) < 0$ *and* $Z''(v) > 0$.

Proof. From the identity $(A + vB)Z(v) = I$ we obtain

$$Z' = -ZBZ, \qquad Z'' = -2ZBZ' = 2ZBZBZ,$$

where $Z' = dZ/dv = [z'_{ij}]$ and $Z'' = dZ'/dv = [z''_{ij}]$. As $B \geq 0$, $B \neq 0$, and $Z(v) > 0$, there follows $Z'(v) < 0$ and $Z''(v) > 0$. □

Lemma 2. *Under the assumptions of Lemma* 1, *let* v_α *be the largest number such that* $\det(A + vB) \neq 0$ *in the interval* $[0, v_\alpha)$. *Then, either* $v_\alpha = +\infty$, *or an element of* $Z(v)$ *must change sign in* $[0, v_\alpha)$.

Proof. As $v \longrightarrow v_\alpha$, at least one entry of $Z(v)$ must become infinite. Otherwise, in any interval $[0, v_\beta)$ where $Z(v) > 0$ we have $Z'(v) < 0$ (Lemma 1); therefore, $Z(v)$ is bounded in $[0, v_\beta)$,

$$0 < Z(v) \leq Z(0) = A^{-1}.$$

It follows that $v^* = \max v_\beta \leq v_\alpha$, with strict inequality if $v^* < +\infty$, because $0 \leq Z(v^*) \leq A^{-1}$. When $v^* < +\infty$, the thesis follows from $Z'(v^*) \leq 0$ and Lemma 1 (note that the entries $z_{ij}(v)$ cannot vanish identically). □

Theorem 1. *Let* v^* *be the largest, possibly infinite, number such that* $Z(v) > 0$ *in* $[0, v^*)$. *Then* v^* *is the limit of the sequence* $\{v_k\}$ *given by*

$$(6)\qquad v_{k+1} = v_k + \min_{i,j;\,w_{kij}>0} z_{kij}/w_{kij}, \qquad k = 0, 1, 2, \dots, n;\ v_0 = 0,$$

where $Z_k = Z(v_k) = [z_{kij}]$, $W_k = -Z'(v_k) = Z_k B Z_k = [w_{kij}]$.

Proof. Let v^*_{ij} be the smallest value of v for which $z_{ij}(v) = 0$, if such a value exists, or $+\infty$ otherwise. We have $v^* = \min_{i,j} v^*_{ij}$. In $[0, v^*)$, the matrix $Z(v)$ does not have singularities (Lemma 2) and its entries are strictly decreasing and convex functions of v (Lemma 1). These regularity conditions on the entries $z_{ij}(v)$ allow us to obtain the sequence $\{v_k\}$, given by (6), as follows: we compute the Newton steps for the elements of the equation $Z(v) = 0$ and use the smallest of them to update v.

The first iteration, with starting value $v_0 = 0$, produces the equations $z_{ij}(0) + v z'_{ij}(0) = 0$, where $z_{ij}(0) > 0$ and $z'_{ij}(0) < 0$. The smallest solution of these equations is the first approximation v_1 in (6) and it is the largest value of v for which

$$Z(0) + vZ'(0) = A^{-1} - vA^{-1}BA^{-1} \geq 0.$$

As $Z(v) > Z(0) + vZ'(0)$ for $0 < v < v^*$, we have $v_1 < v^*_{ij}$, $i, j = 1, 2, \dots, n$; therefore, $0 < v_1 < v^*$ and $Z_1 > 0$, $W_1 > 0$.

The successive approximations v_k are defined as follows. Suppose we have computed the approximation v_k, for some $k > 0$, for which we have $0 < v_k < v^*$, $Z_k > 0$, $W_k > 0$. We compute the Newton steps starting from the value v_k, common to all the equations $z_{ij}(v) = 0$; this produces the equations $z_{ij}(v_k) + (v - v_k)z'_{ij}(v_k) = 0$. The approximation v_{k+1} (the smallest solution of these equations) is the largest value of v for which

$$Z(v_k) + (v - v_k)Z'(v_k) = Z_k - (v - v_k)W_k \geq 0$$

and it is given by (6). As $Z(v) > Z(v_k) + (v - v_k)Z'(v_k)$ for $v_k < v < v^*$, we have $v_{k+1} < v^*_{ij}$, $i, j = 1, 2, \dots, n$; therefore $v_k < v_{k+1} < v^*$ and $Z_{k+1} > 0$, $W_{k+1} > 0$. We conclude that the sequence $\{v_k\}$ is increasing, bounded from above by v^* if $v^* < +\infty$, and convergent to v^* (note that $\{v_k\}$ cannot converge to a limit $v^*_1 < v^*$ since this would imply $(v_{k+1} - v_k) \longrightarrow \min_{ij} z_{ij}(v^*_1)/|z'_{ij}(v^*_1)| > 0)$.

When $v^* = +\infty$, all the entries $z_{ij}(v)$ are positive, strictly decreasing, and convex functions of $v \in [0, +\infty)$ (the only possible solution of each equation $z_{ij}(v) = 0$ is $v^* = +\infty$). If the sequence $\{v_k\}$ were bounded, then it would be convergent: $v_k \to v^*_1 < +\infty$; as above, we would have $(v_{k+1} - v_k) \to$ constant > 0. Thus, $\{v_k\}$ is not bounded and it is diverging monotonically to $+\infty$. $\square$

Remarks. (a) It is possible to show that the sequence $\{v'_k\}$ given by

$$v'_{k+1} = v'_k + \min_{i, j;\, w_{0ij} > 0} z_{kij}/w_{0ij}, \qquad k = 0, 1, 2, \dots; \, v'_0 = 0,$$

is convergent to v^*, if $v^* < +\infty$, or divergent to $+\infty$ otherwise.

(b) Only for very small n (the first few integers) can we obtain the analytic expressions of the entries $z_{ij}(v)$ $(i, j = 1, 2, \dots, n)$ and find their zeros to evaluate v^*. The application of the iterative process (6) involves the numerical computation of the inverses Z_k, and each iteration requires $O(n^3)$ operations; however, the method has been applied successfully with n equal to 30, 40, and 50 (for example, by using matrices from one-dimensional boundary value problems).

(c) We can show the quadratic convergence [3, p. 260] of the process (6) when $v^* < +\infty$ and $Z'(v^*) > 0$. We introduce in (6) z_{kij} obtained from Taylor's formula

$$z_{ij}(v^*) = z_{kij} - (v^* - v_k)w_{kij} + \tfrac{1}{2}(v^* - v_k)^2 z''_{ij}(v_{kij}),$$

where $v_k \le v_{kij} \le v^*$. After some manipulations we have

$$v^* - v_{k+1} = \min_{i,j;\, w_{kij}>0} \left[\tfrac{1}{2}(v^* - v_k)^2 z''_{ij}(v_{kij}) - z_{ij}(v^*)\right] / w_{kij};$$

thus, as $z_{ij}(v^*) \ge 0$ and $w_{kij} > 0$, it follows that

$$s_{k+1} \le \max_{i,j;\, w_{kij}>0} z''_{ij}(v_{kij})/w_{kij} \to \max_{i,j} z''_{ij}(v^*)/|z'_{ij}(v^*)|,$$

where

$$s_{k+1} = (v^* - v_{k+1})/(v^* - v_k)^2. \tag{7}$$

3. The inverse of $C(v) = A + v(B - B^{\mathrm{T}})$

Theorem 2. *Let the symmetric matrix $A + A^{\mathrm{T}}$ be positive definite. Then, in $[0, v^*)$ the spectral radius h of the nonnegative matrix*

$$H(v) = vZ(v)B^{\mathrm{T}} \tag{8}$$

is less than 1, and $C^{-1}(v) \ge Z(v) > 0$.

Proof. The matrix $C(v)$ given by (4) is now written as

$$C(v) = (A + vB)[I - H(v)],$$

where $H(v)$ is given by (8). In $[0, v^*)$ we have $Z(v) > 0$; it follows that $C^{-1}(v) \ge Z(v) > 0$ if the spectral radius $h(v) = r(H)$ of the nonnegative matrix $H(v)$ is less than 1 [5, p. 83]. To the spectral radius h there corresponds an eigenvector $\mathbf{u} \ge 0$; from the eigenvalue equation $vB^{\mathrm{T}}\mathbf{u} = h(A + vB)\mathbf{u}$ we obtain

$$h = v\mathbf{u}^{\mathrm{T}}B\mathbf{u}/(\mathbf{u}^{\mathrm{T}}A\mathbf{u} + v\mathbf{u}^{\mathrm{T}}B\mathbf{u}).$$

We have $\mathbf{u}^{\mathrm{T}}A\mathbf{u} = \frac{1}{2}[\mathbf{u}^{\mathrm{T}}(A + A^{\mathrm{T}})\mathbf{u}] > 0$, because $A + A^{\mathrm{T}}$ is assumed positive definite. Thus, as $v \ge 0$, $\mathbf{u} \ge 0$, $B \ge 0$, it follows that $h < 1$. □

Remarks. By means of simple examples it is possible to show that:

(a) The condition $A + A^{\mathrm{T}}$ positive definite is not necessary to have $h(v) < 1$, $0 \le v < v^*$.

(b) The condition $H(v) \ge 0$, $0 \le v < v^*$, is not sufficient by itself to have $h(v) < 1$.

4. Numerical results

As a sample problem we use the matrix $A + vB$ obtained from a finite difference approximation to (5) using central differences and the trapezium rule.

Here we present the results obtained by assuming in (5) that $p = 1$, $q = 0$, and $K(x, x') = \exp(-(x - x')^2)$ (sample problem 1). In this case, A is a Stieltjes matrix [5, p. 85] and B is a positive matrix. The inverses Z_k are computed by means of the routine LINV2F of the IMSL Library. The results (double-precision computation) are shown in Table 1. The quantities s_k, given by (7), tend to a constant value confirming quadratic convergence. Values of v greater than v^*, for which some computed entries of $Z(v)$ are less than zero are reported in the row $*$.

TABLE 1
Values of v_k and of s_k for the sample problem 1 for different values of the mesh spacing $1/m$.

	$m = 30$		$m = 40$		$m = 50$	
k	v_k	s_k	v_k	s_k	v_k	s_k
0	0.		0.		0.	
1	5.145497	0.0658	5.076475	0.0678	5.035965	0.0690
2	8.172000	0.0491	8.018864	0.0496	7.929456	0.0499
3	8.820264	0.0505	8.633288	0.0510	8.524586	0.0517
4	8.842959	0.0508	8.653839	0.0514	8.543958	0.0517
5	8.842985	0.0508	8.653861	0.0513	8.543978	0.0516
6	8.842985		8.653861		8.543978	
$*$	8.85		8.66		8.55	

TABLE 2
Values of v_k and of s_k for the sample problem 2 for different values of the mesh spacing $1/m$.

	$m = 30$		$m = 40$		$m = 50$	
k	v_k	s_k	v_k	s_k	v_k	s_k
0	0.		0.		0.	
1	0.411695	1.8439	0.299168	2.5543	0.234883	3.2660
2	0.471457	0.2874	0.341517	0.3880	0.267634	0.4885
3	0.472521	0.2899	0.342236	0.3912	0.268175	0.4924
4	0.472521	0.2881	0.342236	0.3884	0.268175	0.5178
5	0.472521		0.342236		0.268175	
$*$	0.48		0.35		0.27	
$**$	0.49		0.36		0.28	

Now we consider the matrix $C(v) = A + v(B - B^{\mathrm{T}})$ obtained by assuming in (5) that $p = 1$, $q = 0$, and $K(x, x') = x - x'$ (sample problem 2). Here the matrix B is the nonnegative contribution due to $K(x, x')$ for $x \geq x'$. The results are shown in Table 2. Values of v greater than v^*, for which some computed entries of $Z(v)$ and of $C^{-1}(v)$ are less than zero are reported in the rows $*$ and $**$, respectively. We note that $[0, v^*)$ is a sufficiently good approximation of the interval in which $C^{-1}(v) > 0$.

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