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August, 1987

CAM Report 87-15

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The Spectrum of a Family of Circulant Preconditioned Toeplitz Systems

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July 1987
Revised August 1987

Abstract. We study the solutions of symmetric positive definite Toeplitz systems $Ax = b$ by preconditioned conjugate gradient method. The preconditioner is the circulant matrix C that minimizes the Frobenius norm $||C - A||_F$, see Chan [5]. Convergence rate is known to be governed by the distribution of the eigenvalues of $C^{-1}A$. For Toeplitz matrix A with entries being Fourier coefficients of a positive function in the Wiener class, we establish the invertiblity of C, find the asymptotic behaviour of the eigenvalues of the preconditioned matrix $C^{-1}A$ as the dimension increases and prove that they are clustered around one.

Abbreviated Title. Circulant Preconditioned Toeplitz Systems

Key words. Toeplitz matrix, circulant matrix, preconditioned conjugate gradient method

AMS(MOS) subject classifications. 65F10,65F15

*This report is supported in part by the NSF Grants DCR84-05506, DCR86-02563 and DOE Grant DE-FG03-87ER25037.

1. Introduction

This paper discusses the solutions to a class of linear systems $A_n x = b$, where A_n are n by n Toeplitz matrices (i.e. the entries of A_n are the same along each diagonals). Direct methods that are based on the Levinson recursion formula are in constant use; see for instance, Levinson [7] and Trench [9]. These methods require $O(n^2)$ operations. Faster algorithms that require $O(n \log^2 n)$ operations have been developed, see Bitmead-Anderson [1] and Brent-Gustavson-Yun [2], but their stability properties for general non-symmetric or indefinite matrices are not yet clearly understood, see Bunch [3].

Strang [8] proposed using preconditioned conjugate gradient method with circulant preconditioners for solving symmetric positive definite Toeplitz systems. The number of operations per iteration will be of order $O(n \log n)$ as circulant systems can be solved efficiently by the Fast Fourier Transform. Chan-Strang [4] then considered using a circulant preconditioner S_n that is obtained by copying the central diagonals of A_n and bringing them around to complete the circulant. More precisely, if $n = 2m$, and the entries a_{ij} of A_n are given by $a_{|i-j|}$ for $0 \le i, j < n$, then the entries $s_{ij} = s_{|i-j|}$ of S_n are given by

$$s_k = \begin{cases} a_k & 0 \le k \le m, \\ a_{n-k} & m \le k < n. \end{cases} \tag{1}$$

It was proved that if the underlying generating function f, which Fourier coefficients give the entries of A_n, is a positive function in the Wiener class, then for n sufficiently large, S_n and S_n^{-1} are uniformly bounded in the l_2 norm and the eigenvalues of the preconditioned matrix $S_n^{-1} A_n$ are clustered around 1.

Chan [5] recently proposed another circulant matrix C_n that is obtained by averaging the corresponding diagonals of A_n with the diagonals of A_n being extended to length n by a wrap-around. More precisely, the entries $c_{ij} = c_{|i-j|}$ of C_n are given by

$$c_k = \frac{k a_{n-k} + (n-k) a_k}{n}, \quad 0 \le k < n. \tag{2}$$

He proved that such C_n minimizes the Frobenius norm $||C - A||_F$ and the experiments showed that the spectrum of the preconditioned matrix $C_n^{-1} A_n$ is also clustered around one with the condition number of $C_n^{-1} A_n$ being often smaller than that of $S_n^{-1} A_n$.

In this paper, we will prove that if the generating function f is a positive function in the Wiener class, then the spectra of the preconditioners C_n and S_n are equal asymptotically. In particular, we will show that for n sufficiently large, C_n and C_n^{-1} are uniformly bounded in the l_2 norm and the eigenvalues of the preconditioned matrix $C_n^{-1} A_n$ are clustered around one. Hence, if the conjugate gradient method is applied to solve this preconditioned system, we can expect the method to have fast convergence.

2. The Spectrum of the Preconditioned Matrix $C_n^{-1} A_n$

Let us begin by supposing that the Toeplitz matrices A_n are finite sections of a fixed singly infinite positive definite matrix A_∞, see Chan-Strang [4]. Thus the (i,j)-th entries of A_n and A_∞ are $a_{|i-j|}$. We associate to A_∞ the generating function

$$f(\theta) = \sum_{-\infty}^{\infty} a_{|k|} e^{-ik\theta},$$

defined on $[0, 2\pi)$. We will assume that f is a positive function in the Wiener class, i.e. the sequence $\{a_k\}$ is in l_1. It follows easily that, see for instance, Grenander-Szego [6], A_n are symmetric positive definite matrices for all n. Moreover, if

$$0 < f_{\min} < f < f_{\max} < \infty, \tag{3}$$

then the spectrum $\sigma(A_n)$ of A_n will lie in $[f_{\min}, f_{\max}]$.

We now show that the spectra of C_n and S_n are asymptotically the same. More precisely, we have

Lemma 1. *Let the generating function f be a positive function in the Wiener class, then*

$$\lim_{n \to \infty} \rho\left(S_n - C_n\right) = 0,$$

where $\rho(\cdot)$ denotes the spectral radius.

Proof: By (1) and (2), it is clear that $B_n \equiv S_n - C_n$ is circulant with entries

$$b_k = \begin{cases} \dfrac{k}{n}(a_k - a_{n-k}) & 0 \le k \le m, \\ \dfrac{n-k}{n}(a_{n-k} - a_k) & m \le k < n. \end{cases}$$

Here for simplicity, we are still assuming $n = 2m$. Using the fact that the j-th eigenvalue $\lambda_j(B_n)$ of B_n is given by $\sum_{k=0}^{n-1} b_k e^{2\pi ijk/n}$, we have

$$\lambda_j(B_n) = 2\sum_{k=1}^{m-1} \frac{k}{n}(a_k - a_{n-k})\cos(2\pi jk/n).$$

This implies

$$\rho(B_n) \le 2\sum_{k=1}^{m-1}\frac{k}{n}|a_k| \; + \; 2\sum_{k=m+1}^{n-1}|a_k|.$$

However, since f is in the Wiener class, hence for all $\epsilon > 0$, we can always find an $M_1 > 0$ and an $M_2 > M_1$, such that

$$\sum_{k=M_1+1}^{\infty}|a_k| < \epsilon/6 \quad \text{and} \quad \frac{1}{M_2}\sum_{k=1}^{M_1} k|a_k| < \epsilon/6.$$

Thus for all $m > M_2$,

$$\rho(B_n) < \frac{2}{M_2}\sum_{k=1}^{M_1} k|a_k| + 2\sum_{k=M_1+1}^{m-1}|a_k| + 2\sum_{k=m+1}^{\infty}|a_k| < \epsilon. \quad \square$$

We remark that if f is positive and is in the Wiener class, then for n sufficiently large, S_n and S_n^{-1} are uniformly bounded in the l_2 norm, see Chan-Strang [4, Theorem 1]. Moreover, if (3) holds, then the spectrum $\sigma(S_n)$ lies in $[f_{\min}, f_{\max}]$ too. Using Lemma 1, we thus have,

Theorem 1. *Let f be a positive function in the Wiener class, then for all n sufficiently large, the circulant matrices C_n and C_n^{-1} are uniformly bounded in the l_2 norm. Moreover, $\sigma(C_n)$ lies in $[f_{\min}, f_{\max}]$.*

To prove that the spectrum of $C_n^{-1}A_n$ is clustered around 1, we first recall that the spectrum of $A_n - S_n$ is clustered around zero:

Lemma 2 [4, Theorem 4]. *Let f be a positive function in the Wiener class, then for all $\epsilon > 0$, there exist $N, M > 0$, such that for all $n > N$, at most M eigenvalues of $A_n - S_n$ have absolute value larger than ϵ.*

Notice that since

$$C_n^{-1}A_n = I_n + C_n^{-1}(A_n - S_n) + C_n^{-1}(S_n - C_n),$$

where I_n is the n by n identity matrix, hence, we have

Theorem 2. *Let f be a positive function in the Wiener class, then for all $\epsilon > 0$, there exist $N, M > 0$, such that for all $n > N$, at most M eigenvalues of $C_n^{-1}A_n - I_n$ have absolute value larger than ϵ.*

Thus the spectrum of $C_n^{-1}A_n$ is clustered around 1 for sufficiently large n. This is consistent with the numerical results obtained in Chan [5]. We note that since the spectra of $C_n^{-1}A_n$ and $S_n^{-1}A_n$ are equal asymptotically, we expect the convergence rates of the conjugate gradient method applied to $S_n^{-1}A_n$ and $C_n^{-1}A_n$ will be roughly the same for n sufficiently large. In particular, both will converge superlinearly, see Chan-Strang [4] and the numerical results below.

3. Numerical Results and Concluding Remarks

For f in the Wiener class, the numerical results in Chan [5] showed that the spectrum of $S_n^{-1}A_n$ is more clustered than that of $C_n^{-1}A_n$. This phenomenon is more pronounced when a_k decreases more rapidly with k. However, it was also observed that in these cases, $C_n^{-1}A_n$ has a smaller condition number than $S_n^{-1}A_n$.

To test the convergence rates of both preconditioners, we apply the preconditioned conjugate gradient method on $A_n x = b$ with $a_k = (1+k)^{-1.1}$. We note that the generating function of A_n is in the Wiener class. The spectra of A_n, $S_n^{-1}A_n$ and $C_n^{-1}A_n$ for $n = 32$ are given in Figure 1. Table 1 shows the number of iterations required to get $||r||_2 < 10^{-7}$. Here r is the residual vector and $||\cdot||_2$ is the normalized l_2 norm. We use the vector of all ones for the right hand side b, and the zero vector as our initial guess. We see that as n increases, the number of iterations increases for the original matrix A_n, while it stays almost the same for the preconditioned matrices. Moreover, both preconditioned systems converge at the same rate for large n.

n	A_n	$S_n^{-1}A_n$	$C_n^{-1}A_n$
8	4	4	4
16	8	5	4
32	11	5	5
64	14	5	5

Table 1. Number of Iterations for Different Systems

We finally emphasize that since C_n is defined in terms of averaging the diagonals of A_n, it can be used for general non-Toeplitz matrix A_n. Thus if A_n is nearly Toeplitz, say a low rank perturbation of a Toeplitz matrix, then C_n may still be a good preconditioner for A_n. As an example, consider the one-dimensional equation $d^2u/dx^2 + u = f$ with Neumann boundary condition. Let A_n be the discretization matrix of the equation by the usual centered second order difference scheme. We note that A_n is non-Toeplitz and the system can be solved easily by direct methods. However, to illustrate our point, we compute the spectra of A_n and $C_n^{-1}A_n$ here. For $n = 32$, they are given in Figure 2. We see that the spectrum of the preconditioned matrix is highly clustered.

Acknowledgement

The author acknowledges helpful discussions with Prof. Tony Chan of UCLA and Prof. Zhengfang Zhou of MIT.

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Figure 1. Comparison of Spectra with a(k)=(1+k)^(-1.1)

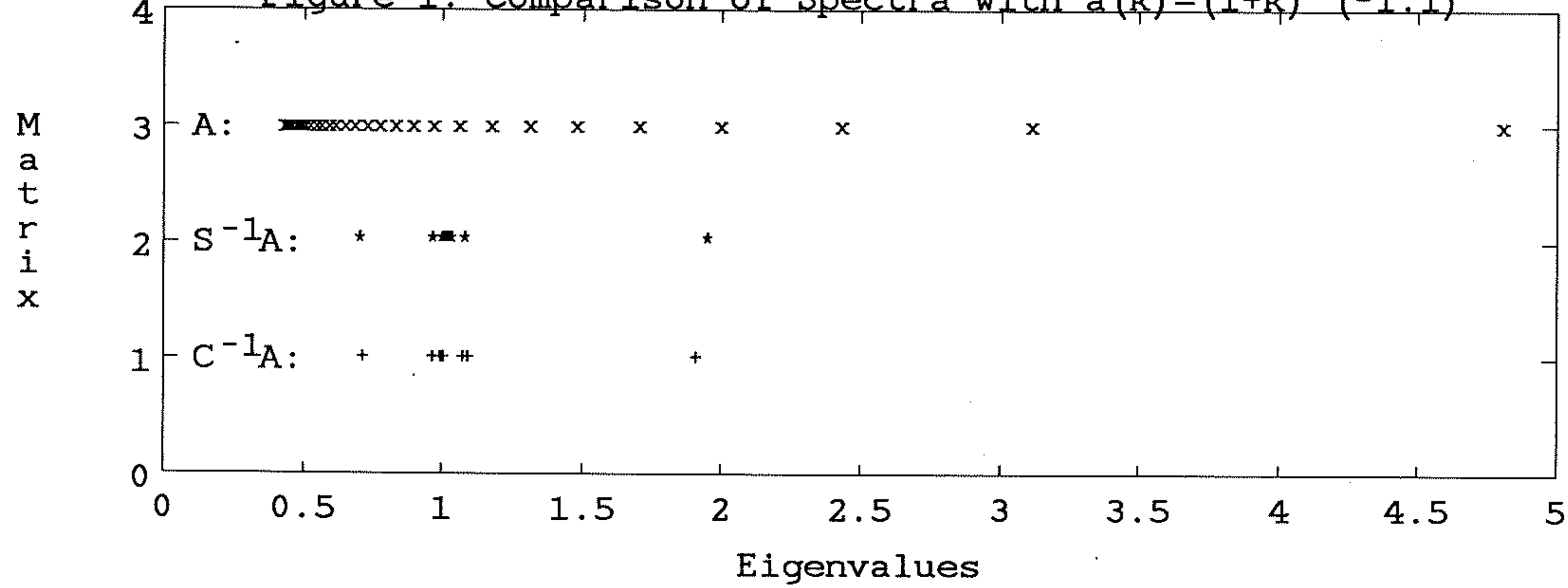

Figure 2. Spectra of the Neumann Problem