Factorization of Multivariate Positive Laurent Polynomials

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**Abstract.** Recently Dritschel proves that any positive multivariate Laurent polynomial can be factorized into a sum of square magnitudes of polynomials. We first give another proof of the Dritschel theorem. Our proof is based on the univariate matrix Féjér-Riesz theorem. Then we discuss a computational method to find approximates of polynomial matrix factorization. Some numerical examples will be shown. Finally we discuss how to compute nonnegative Laurent polynomial factorizations in the multivariate setting.

§1. Introduction

We are interested in computing factorizations of nonnegative Laurent polynomials into sum of squares of polynomials. That is, let

\[ P(z) = \sum_{k=-n}^{n} p_k z^k \]

be a Laurent polynomial, where \( z = e^{i\theta} \). Suppose that \( P(z) \geq 0 \) for \( |z| = 1 \). One would ask if there exists a polynomial \( Q(z) = \sum_{k=0}^{n} q_k z^k \) such that

\[ P(z) = Q(z)^* Q(z), \]

where \( Q(z)^* \) denotes the complex conjugate of \( Q(z) \). This is the well-known Féjér-Riesz factorization problem and it was resolved by Fejér [F'15] and by Riesz [R'15]. A natural question is whether the results of Fejér and Riesz can be extended to the multivariate setting. More generally, given a nonnegative multivariate trigonometric polynomial \( P(z) := P(z_1, z_2, \cdots, z_d) \) of coordinate degrees \( \leq n \), does there exist a finite number of polynomials \( Q_k(z) \) such that

\[ P(z) = \sum_{k} Q_k^*(z)Q_k(z), \]

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i.e., can $P(z)$ be written as a sum of square magnitudes (sosm) of polynomials. There is a vast amount of literature related to the study of this problem and the results relevant to this paper may be summarized as follows:

1° When $P(z)$ is nonnegative on the multi-torus $|z_1| = |z_2| = \cdots = |z_d| = 1$ and the coordinate degrees of $Q_k$ are less than or equal to $n$, then the answer to the question is negative. (See [Calderon and Pepinsky’52] and [Rudin’63].)

2° When $P(z)$ is strictly positive on the multi-torus and the coordinate degrees of $Q_k$ are not specified, Dritschel has shown that the answer to the question is positive ([Dritschel’04]). However the nonnegative case remains unresolved.

3° In the bivariate setting, Geronimo and Woerdeman gave a necessary and sufficient condition in order for $P(z) = |Q(z)|^2$, where $Q(z)$ is a stable polynomial, i.e., $Q(z) \neq 0$ inside and on the bi-torus ([Geronimo and Woerdeman’04]).

4° In the bivariate setting, there exist rational Laurent polynomials $Q_k(z)$ such that (2) holds. Furthermore, $Q_k$ can be so chosen that the determinants of $Q_k$ containing only one variable Laurent polynomials (cf. [Basu’01]).

5° In [McLean and Woerdeman’01], an algorithm was proposed to find polynomials $P_k$ such that $P = \sum_k |P_k|^2$. The algorithm uses the so-called semi-definite programming.

Although the mathematical problem appears to be theoretical, it has many applications in engineering, e.g., the design of autoregressive filters, construction of orthonormal wavelets (cf. [Daubechies’92]), construction of tight wavelet framelets (cf. [Lai and Stoeckler’04]), spectral estimation in control theory (cf. [Sayed and Kailath’01]) and many other engineering applications mentioned in [McLean and Woerdeman’01]. Thus, how to compute such factorization polynomials $Q_1, Q_2, \cdots$, is interesting and useful for applications. In this paper, we discuss a symbol approximation method studied in [Lai’94] for computing such factorizations. The method was originally intended for factorizing any nonnegative Laurent polynomials in the univariate setting. We use the ideas to give Dritschel’s theorem another proof. The proof provides a computational method to factor $P(z)$ into $Q_k(z)$’s. The paper is organized as follows. In section 2, we first give a different proof of Dritschel’s Theorem. A key in the proof is to factorize univariate Laurent polynomial matrices. In section 3, we discuss how to compute the factorization of positive Laurent polynomials matrices. The method used by [Lai’94] to compute approximate factorizations is extended to the matrix case. Then in section 4, some numerical examples are computed following the procedure in §2 and §3. Finally in section 5, the nonegative case is considered.

§2. Dritschel’s Theorem

We begin with reviewing the concept of the symbols of bi-infinite Toeplitz matrices and its properties. For a given univariate Laurent polynomial $P(z) = \sum_{k=-n}^{n} p_k z^k$, we may view $P(z)$ as the symbol of a bi-infinite Toeplitz matrix $\mathcal{P} := (p_{i-j})_{i,j \in \mathbb{Z}}$. 


Indeed, for any absolutely summable sequence $x = (x_i)_{i \in \mathbb{Z}}$, i.e., $\sum_{i \in \mathbb{Z}} |x_i| < \infty$, let $F(x) = \sum_{j \in \mathbb{Z}} x_j z^j$ be the discrete Fourier transform (or z-transform) of $x$. Let $y = P x$, then it is easy to see that

$$F(y) = P(z) F(x).$$

If the matrix $P$ has a factorization $Q$ which is a banded upper triangular Toeplitz matrix such that

$$P = Q^\dagger Q,$$

the discrete Fourier transform of $y = Q Q^\dagger x$ is $F(y) = Q(z)^* Q(z) F(x)$, where $Q^\dagger$ denotes the complex conjugate transpose of $Q$. Thus, finding $P(z) = Q(z)^* Q(z)$ is equivalent to finding a banded upper triangular Toeplitz matrix $Q$ such that $P = Q^\dagger Q$.

It is easy to show that if $P(z) \geq 0$ for all $|z| = 1$, then $P$ is Hermitian and nonnegative definite. Clearly, $P$ is Hermitian since $P(z)$ is real. Furthermore for any absolutely summable sequence $x$, we need to show that $x^\dagger P x \geq 0$. Again writing $y = P x$, we know that

$$x^\dagger y = \frac{1}{2\pi} \int_0^{2\pi} F(x) F(y) d\theta$$

where $z = e^{i\theta}$ and it follows that

$$x^\dagger P x = \frac{1}{2\pi} \int_0^{2\pi} |F(x)|^2 P(z) d\theta \geq 0$$

for any nonzero sequence $x$. In particular, for

$$x = (\cdots, 0, x_{-N}, \cdots, x_0, \cdots, x_N, 0, \cdots)^T,$$

the left-hand side in the above inequality gives $x^\dagger P_N x$, where $P_N$ is a central section of $P$. The above argument shows that $P_N$ is nonnegative definite.

In the following we will assume that $P(z)$ is strictly positive, in the sense that there exists a positive number $\epsilon > 0$ such that $P(z) \geq \epsilon$. When $P(z)$ is a matrix, we mean that $P(z) \geq \epsilon I$, where $I$ is the identity matrix of the same size as that of $P(z)$. When $P(z)$ is strictly positive, we have

$$x^\dagger P x = \frac{1}{2\pi} \int_0^{2\pi} |F(x)|^2 P(z) d\theta \geq \epsilon \|x\|^2.$$

It follows that if $P(z) \geq \epsilon > 0$, then $P_N \geq \epsilon > 0$.

We now consider the factorization of multivariate Laurent polynomials. Let us begin with a bivariate Laurent polynomial $P(z_1, z_2)$ first. That is, let

$$P(z_1, z_2) = \sum_{j=-n}^{n} \sum_{k=-n}^{n} p_{jk} z_1^j z_2^k \geq 0$$

for some coefficients $p_{jk}$.
be a Laurent polynomial of coordinate degrees \( \leq n \). We would like to find a finite number of polynomials \( Q_k \) such that

\[
P(z_1, z_2) = \sum_k |Q_k(z_1, z_2)|^2.
\]

Denote by \( z_1 = [1, z_1, z_1^2, \ldots, z_1^n]^T \) and write

\[
P(z_1, z_2) = z_1^\dagger \tilde{P}(z_2) z_1
\]

for a Hermitian matrix \( \tilde{P}(z_2) = \sum_{k=-n}^n \tilde{p}_k z_2^k \), where each \( \tilde{p}_k \) is an \( (n+1) \times (n+1) \) Toeplitz matrix. With a slight modification of an observation of [McLean and Woerdeman'01, Theorem 2.1], we note that there are many ways to write \( \tilde{P}(z_2) \). If there is one \( \tilde{P}(z_2) \) which is nonnegative definite then we can use the matrix Féjer-Riesz factorization (cf. e.g., in [Helson'64], [Mclean-Woerdeman'01], see also section 3) to find \( \tilde{Q}(z_2) \) such that

\[
\tilde{P}(z_2) = \tilde{Q}^\dagger(z_2)\tilde{Q}(z_2).
\]

That is, we have

\[
P(z_1, z_2) = (\tilde{Q}(z_2)z_1)\dagger \tilde{Q}(z_2)z_1
\]

which is clearly a sum of squares of polynomials.

The above discussion can be generalized to the multivariate setting and using an observation of [Dritschel'04] to the case that the size of \( \tilde{P}(z_2) \) is larger than \( (n+1) \times (n+1) \). For simplicity, let us consider a trivariate Laurent polynomial \( P(z_1, z_2, z_3) \) in \( z_1 = e^{i\theta_1}, z_2 = e^{i\theta_2}, z_3 = e^{i\theta_3} \) of coordinate degrees \( \leq n \). We first write \( P(z_1, z_2, z_3) \) in a matrix format:

\[
P(z_1, z_2, z_3) = \sum_{-n}^n p_k(z_2, z_3) z_1^k = z_1^\dagger \hat{P}(z_2, z_3) z_1,
\]

with

\[
z_1 = [1, z_1, \ldots, z_1^{m_1}]^T
\]

and \( m_1 \geq n \). There are many ways to write \( \hat{P}(z_2, z_3) \). To capture this define the set of matrices

\[
\mathcal{F}(z_2, z_3) = \{(p_{i,j}(z_2, z_3)) \, 0 \leq i, j \leq m_1 : \sum_{i-j=k \atop |k| \leq m_1} p_{i,j}(z_2, z_3) = p_k(z_2, z_3)\}.
\]
Note that the matrices in $\mathcal{F}$ are banded since $p_k = 0$, $|k| > n$. We look for a matrix $\hat{P}(z_2, z_3)$ in $\mathcal{F}$ that is positive definite for $|z_2| = 1 = |z_3|$. The polynomial matrix $\hat{P}(z_2, z_3)$ can be written as

$$\hat{P}(z_2, z_3) = \sum_{k=-n}^{n} \hat{P}_k(z_3) z_2^k,$$

where each $\hat{P}_k(z_3)$ is an $(m_1 + 1) \times (m_1 + 1)$ Toeplitz matrix. Thus we can write

$$\hat{P}(z_2, z_3) = z_2^\dagger \bar{P}(z_3) z_2,$$

where $z_2 = [I_{m_1}, z_2 I_{m_1}, \ldots, z_2^m I_{m_1}]^T$, with $I_{m_1}$ being the $(m_1 + 1) \times (m_1 + 1)$ identity matrix and $m_2 \geq n$. The polynomial $\bar{P}(z_3)$ is a matrix polynomial of size $(m_1 + 1)(m_2 + 1) \times (m_1 + 1)(m_2 + 1)$. If it is nonnegative definite we can factor it into a polynomial matrix $Q(z_3)$, i.e., $\bar{P}(z_3) = Q(z_3)^\dagger Q(z_3)$ by the matrix Féjer-Riesz theorem (cf. [Helson’64] or [Mclean and Woerdeman’01]) then we have

$$P(z_1, z_2, z_3) = (Q(z_3)z_2 z_1)^\dagger (Q(z_3)z_2 z_1)$$

which is a sum of square magnitudes of polynomials in $z_1, z_2, z_3$.

Our task then is to produce a positive definite polynomial matrix for any given positive multivariate Laurent polynomial. We resume our discussion on the two variable case again and rewrite $P(z_1, z_2)$ as follows:

$$P(z_1, z_2) = \sum_{k=-n_1}^{n_1} p_k(z_2) z_1^k = z_{m_1}^\dagger P_{m_1}(z_2) z_{m_1}$$

where $m_1 \geq n_1$, $z_{m_1} = [1, z_1, z_1^2, \ldots, z_1^{m_1}]^T$, and

$$P_{m_1}(z_2) = [p_{jk}(z_2)]_{0 \leq j, k \leq m_1}$$

with polynomial entries $p_{j,k}(z_2)$ given by

$$p_{j,k}(z_2) = \frac{1}{m_1 + 1 - |j - k|} p_{k-j}(z_2), \forall j, k = 0, \ldots, m_1.$$

Note that $p_{j,k}(z_2) = 0$ for $|j - k| > n_1$. Under this decomposition we can show that for some $m_1$ large enough, the matrix $P_{m_1}(z_2)$ will be positive definite when
$P(z_1, z_2)$ is positive definite. To see this we note $P(z_1, z_2)$ is the symbol of the following bi-infinite Toeplitz matrix,

$$
\begin{bmatrix}
\cdots & \cdots & \cdots & \cdots & \cdots \\
\cdots & p_0(z_2) & p_{-1}(z_2) & \cdots & p_{-n}(z_2) & 0 & \cdots \\
\cdots & p_1(z_2) & p_0(z_2) & \cdots & \cdots & \cdots & \cdots \\
\cdots & p_2(z_2) & p_1(z_2) & \cdots & \cdots & \cdots & \cdots \\
\cdots & \vdots & \vdots & \ddots & \ddots & \ddots & \ddots \\
\cdots & p_n(z_2) & p_{n-1}(z_2) & \cdots & \cdots & \cdots & \cdots 
\end{bmatrix}
$$

(4)

The positivity of $P(z_1, z_2)$ implies that any central section of the this matrix, i.e., any square block with the diagonal consistent with the main diagonal

$$\text{diag}(\cdots, p_0(z_2), p_0(z_2), p_0(w_2), \cdots)$$

is positive as explained at the beginning of this section. Typically, we have

$$p_0(z_2) > 0, \quad \begin{bmatrix} p_0(z_2) & p_{-1}(z_2) \\ p_1(z_2) & p_0(z_2) \end{bmatrix} > 0, \quad \begin{bmatrix} p_0(z_2) & p_{-1}(z_2) & p_{-2}(z_2) \\ p_1(z_2) & p_0(z_2) & p_{-1}(z_2) \\ p_2(z_2) & p_1(z_2) & p_0(z_2) \end{bmatrix} > 0, \cdots.$$ 

For convenience, we denote by $\mathcal{P}_2$ and $\mathcal{P}_3$ to be the $2 \times 2$ and $3 \times 3$ matrices above, respectively. In general, we use $\mathcal{P}_k$ to denote the $k \times k$ central block matrix from the bi-infinite Toeplitz matrix (4) above.

We now look at the matrix $P_{m_1}(z_2)$ given by,

$$
\begin{bmatrix}
\frac{1}{m_1+1}p_0(z_2) & \frac{1}{m_1}p_{-1}(z_2) & \cdots & \frac{1}{m_1+1-n_1}p_{-n_1}(z_2) & 0 & \cdots \\
\frac{1}{m_1}p_1(z_2) & \frac{1}{m_1+1}p_0(z_2) & \frac{1}{m_1}p_{-1}(z_2) & \cdots & \cdots & \cdots \\
\frac{1}{m_1-1}p_2(z_2) & \frac{1}{m_1}p_1(z_2) & \cdots & \cdots & \cdots & \cdots \\
\vdots & \vdots & \ddots & \ddots & \ddots & \ddots \\
\frac{1}{m_1+1-m_1}p_{n_1}(z_2) & \cdots & \cdots & \cdots & \cdots & \\frac{1}{m_1}p_0(z_2) \\
0 & \cdots & \cdots & \cdots & \cdots & \frac{1}{m_1+1}p_0(z_2) \n\end{bmatrix}
$$

Note that each diagonal sums to $p_{i-j}(z_2)$ so $P_{m_1}$ is in $\mathcal{F}(z_2)$ where $\mathcal{F}(z_2)$ is defined as above with the obvious modifications. With $x = [x_0, x_1, \cdots, x_{m_1}]^T$, we need to prove that $x^*P_{m_1}(z_2)x > 0$. First we write

$$
\begin{align*}
x^*P_{m_1}(z_2)x &= \frac{1}{m_1+1}x^*\mathcal{P}_{m_1}x + \frac{1}{m_1+1}x^*R_{m_1}x
\end{align*}
$$
with a remainder matrix $R_{m_1}$. The $\ell_2$ norm of $R_{m_1}$ can be estimated using the column norm to give

$$\|R_{m_1}\|_2 \leq \frac{n_1(n_1 + 1)C_1}{2(m_1 - n_1)},$$

where $C_1 = \sup_{i,|z_2|=1}|p_i(z_2)|$. If $P(z_1, z_2) \geq \epsilon$ then $x^*P_{m_1}x \geq \epsilon\|x\|_2$, so that if $\frac{n_1(n_1 + 1)C_1}{2(m_1 - n_1)} < \epsilon$, then $x^*P_{m_1}(z_2)x > 0$. Then an application of the matrix Riesz-Fejer Theorem yields

**Theorem 2.1.** Let $P(z_1, z_2) = \sum_{k=-n_1}^{n_1} p_k(z_2)z_1^k \geq \epsilon > 0$ be strictly positive on bi-torus $|z| = 1 = |z_2|$. Then $P(z_1, z_2)$ can be factored into a sum of squares of polynomials in $z_1$ and $z_2$. The total number of terms in the sum is less than or equal to $m_1 + 1$ with $m_1$ being an integer such that

$$\frac{n_1(n_1 + 1)C_1}{2(m_1 - n_1)} < \epsilon,$$

and the degrees of each of the polynomials is bounded by $m_1$ in $z_1$ and $n_2$ in $z_2$.

We remark that when $P(z_1, z_2)$ has different coordinate degrees $n_1, n_2$, it may be worthwhile depending upon $C_1$ to choose the smaller among $n_1$ and $n_2$ in order to have a fewer terms in the sum of square magnitudes of polynomials for $P(z_1, z_2)$.

Next we generalize the result in Theorem 2.1 to the multivariate setting which is known from [Dritschel'04].

**Theorem 2.2 (Dritschel).** Let $P(z_1, \cdots, z_d)$ be a multivariate Laurent polynomial which is strictly positive on the multivariate torus $|z_1| = |z_2| = \cdots = |z_d| = 1$, where $d \geq 2$ is an integer. Then $P(z, w)$ can be expressed as a sum of square magnitudes of polynomials in $z_1, \cdots, z_d$.

**Proof:** We shall use the arguments in the proof of the previous Theorem. Write $P(z_1, z_2, \cdots, z_d) = P(z_1, z) = \sum_{j=-n_1}^{n_1} p_j(z)z_1^j > 0$, where $z$ is the usual multivariable notation beginning with $z_2$. We know that $P(z_1, z)$ is the symbol of the bi-infinite Toeplitz matrix given by (4) with $z_2$ replaced by the multivariable $z$. It follows that any central section along the main diagonal is strictly positive definite as explained before. Write

$$P(z_1, z) = z_1^*P_{m_1}(z)z_1,$$

where $z_1$ given by equation (3) and $P_{m_1}(z) = [p_{j,k}]_{0 \leq j, k \leq m_1}$ is a matrix of size $(m_1 + 1) \times (m_1 + 1)$ with entries

$$p_{j,k} = \frac{1}{m_1 + 1 - |j - k|} p_{j-k}(z), \quad \forall j, k = 0, 1, \cdots, m_1.$$
If $P > \epsilon$ the argument in Theorem 2.1 shows that for $m_1$ large enough there is an $\epsilon_1 > 0$ such that $x^\dagger P_{m_1}(z)x > \epsilon_1$ on the d-1 torus if $\frac{n_1(n_1 + 1)\hat{C}_1}{2m_1 - n_1} < \epsilon$, where in this case $\hat{C}_1 = \sup_{i,|z_j|=1,j=2,...,d}|p_i(z)|$. Write $P_{m_1}(z_2, z') = \sum_{k=-n_2}^{n_2} \hat{p}_k(z') z_2^k$, where $\hat{p}_k$ are $(m_1 + 1) \times (m_1 + 1)$ Toeplitz matrices and $z' = (z_3, \ldots, z_d)$. Now set

$$\hat{p}_{jk} = \frac{1}{m_2 + 1 - |j - k|} \hat{p}_{j-k}(z'), \quad \forall j, k = 0, \ldots, m_2$$

with $m_2 \geq m_1$ and $P_{m_2}(z') = [\hat{p}_{j,k}]_{0 \leq j, k \leq m_2}$. As above we have that

$$x^\dagger P_{m_2}x = \frac{1}{m_2 + 1} x^\dagger P_{m_2}x + \frac{1}{m_2 + 1} x^\dagger R_{m_2}x.$$ 

As above the norm of $R_{m_2}$ can be bounded by

$$\|R_{m_2}\|_2 \leq \frac{n_2(n_2 + 1)C_2}{2(m_2 - n_2)},$$

where $C_2 = \sup_{i,|z_j|=\cdots|z_d|=1} \|\hat{p}_i(z')\|_2$. Thus for $m_2$ sufficiently large, $P_{m_2}$ is a positive matrix polynomial. We continue the process until we arrive at the positive trigonometric matrix polynomial $P_{m_2}(z)$ which can be factored by the matrix Féjer-Reisz Theorem. We have thus established the proof. □

Note that the number of factors will be $(m_1 + 1)(m_2 + 1) \cdots (m_{d-1} + 1)$ and the degrees of the polynomials at most $m_1$ for $z_1$ ... $m_{d-1}$ for $z_{d-1}$ and $n_d$ for $z_d$. We note that we could have avoided the use of the matrix Fejér-Riesz lemma by eliminating all variables then using a square root of a positive matrix (see Mclean and Woerdeman’01). We will consider an alternative computationally attractive method for computing factorizations in the next section.

§3. Computing Approximate Factorizations

As shown in the previous section, an important step in the factorization of multivariate Laurent polynomials is to compute the factorization of univariate polynomial matrices. Recall a computational algorithm for factorizations of one variable trigonometric polynomials was exploited in [Lai’94]. This method can be developed to factorize polynomial matrices in the univariate setting. Let us first introduce some necessary notation and definitions in order to explain the method in more detail.

Let $\ell_2$ stand for the space of all square summable sequences. Let $\|x\|_2$ denote the standard norm on $\ell_2$. We note that for any operator $A$ from $\ell^2 \mapsto \ell^2$, $A$ can be expressed by a bi-infinite matrix.
Definition 3.1. A bi-infinite matrix $A = (a_{ik})_{i,k \in \mathbb{Z}}$ is said to be of exponential decay off its diagonal if

$$\|a_{ik}\|_2 \leq K r^{|i-k|}$$

for some constant $K$ and $r \in (0, 1)$, where $\mathbb{Z}$ is the collection of all integers. $A$ is banded with band width $b$ if $a_{ik} = 0$ for all $i, k \in \mathbb{Z}$ with $|i - k| > b$.

If $A$ is a positive operator, then there exists the unique positive bi-infinite square root matrix $Q$ of $A$ such that $Q^2 = A$. If $A = B^\dagger B$ for another bi-infinite matrix $B$, then there exists a unitary matrix $U$ such that $B = UQ$.

Recall from the previous section that given any Laurent polynomial $P(z)$, we can view $P(z)$ to be the symbol of a bi-infinite Toeplitz matrix $P$. The computational scheme introduced in [Lai‘94] roughly speaking is to choose a central section $P_N = (p_{j-k})_{-N \leq j, k \leq N}$ of matrix $P$ and compute a Cholesky factorization i.e. $P_N = C_N^\dagger C_N$ where $C_N$ is an upper triangular matrix with positive diagonal entries, if $P_N$ is positive definite or use the singular value decomposition (SVD) to find $Q_N$ if $P_N$ is nonnegative definite and then find a Householder matrix $H_N$ such that $C_N = H_N Q_N$ is upper triangular. Then the nonzero entries in the middle row of $C_N$ approximate that in the middle row (in fact any row) of $C$ whose symbol $C(z)$ is a factorization of $P(z)$, i.e., $P(z) = C(z)^* C(z)$.

For the extension of this method to matrix polynomials, let

$$\ell_k^m = \{ x = \{ x_i \}_{i \in \mathbb{Z}}, x_i \in \mathbb{R}^m, \| x \|_k < \infty \}, \quad k = 1, 2$$

and $B(\ell_2^m)$ be the set of bounded linear operators on $\ell_2^m$. Let $\Pi_N \in B(\ell_2^m)$ be the projection given by

$$\Pi_N x = y, \quad y = \{ y_i \} : y_i = 0, |i| > N, y_i = x_i, |i| \leq N.$$

If $P \in B(\ell_2^m)$ is positive definite we will be interested in considering the $(2N + 1)m \times (2N + 1)m$ submatrix of $P$ centered at the index zero which will be called the Nth central section and which is also positive definite. We will also be interested in extensions of various finite matrices $A_N$ to $B(\ell_2^m)$ given by

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & A_N & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

which with a slight abuse of notation will also be called $A_N$.

Consider the matrix polynomial $P(z) = \sum_{j=-n}^{n} p_j z^j$ with matrix coefficients $p_k$’s of size $m \times m$, then $P = (p_{i-j})_{i,j \in \mathbb{Z}} \in B(\ell_2^m)$ defined by $m \times m$ matrix blocks $p_k, -n \leq k \leq n$ is a bi-infinite block Toeplitz matrix whose symbol is $P(z)$. As shown earlier if $P(z)$ is Hermitian nonnegative definite, so is $P$. Let $C(z)$ be a
factorization of $P(z)$ i.e., $P(z) = C(z)^\dagger C(z)$, then $P = C^\dagger C$, where $C$ is a bi-infinite upper triangular banded block Toeplitz matrix associated with $C(z)$. On the other hand, if $P = C^\dagger C$ for a upper triangular banded block Toeplitz matrix, then the symbol $C(z)$ of $C$ satisfies $P(z) = C(z)^\dagger C(z)$. If $P(z)$ is positive definite then it follows from the matrix Fejér-Riesz Lemma [Helson’64], [Mclean-Woerdeman’01] that it is possible to choose $C$ so that it has positive diagonal entries. We shall prove the following,

**Theorem 3.1.** Let $P(z) = \sum_{n}^{\infty} p_k z^k$ be an $m \times m$ matrix polynomial that is positive definite for $|z| = 1$. Let $P = (p_{i-j})_{i,j \in \mathbb{Z}} = C^\dagger C$ where $C$ is an upper triangular banded block Toeplitz with positive diagonal entries, $P_N$ be the $N$th central section of $P$, and $C_N$ its Cholesky factor (which we extend as described above). Then

$$\| (\hat{C}_N - C_N) \delta \|_2 < K \rho^N,$$

for some $\rho \in (0, 1)$, where $\delta \in \mathbb{l}_2^m$ is a vector with a finite number of nonzero entries.

**Remark** For the numerical computation below we will choose $\delta$ with zero components except for $\delta_0 = I_m$, the $m \times m$ identity matrix.

The proof of Theorem 3.1 is based upon the following Theorem 3.2 and Lemmas 3.3 and 3.4.

**Theorem 3.2.** Suppose that $A \in B(\ell_2)$ is a positive banded operator such that $\|A - I\|_2 < 1$. Let $Q$ be the unique positive square root of $A$, $A_N$ be a central section, and $Q_N$ be the positive matrix such that $Q_N^2 = A_N$. Then

$$\| (Q - Q_N) \delta \|_2 \leq K \lambda^N$$

for some $\lambda \in (0, 1)$ and a positive constant $K$. In equation (6) $\delta \in l_2$ is any vector with a fixed number of nonzero entries.

To prove the above Theorem, we begin with the following lemmas.

**Lemma 3.3.** Suppose that $A$ is banded with bandwidth $b$ and $\|A - I\|_2 \leq r < 1$. Then $Q = (q_{i,k})_{i,k \in \mathbb{Z}}$ then $|q_{i,k}| \leq Kr^{i-k}$. If $A$ is invertible, then the entries of $Q^{-1}$ satisfy a similar bound.

**Proof:** We only prove the exponential decay property of $Q$. The proof of that of $Q^{-1}$ is similar. The uniqueness of $Q$ and the convergence of the following series

$$\sum_{i=0}^{\infty} (-1)^i \frac{(2i - 3)!!}{(2i)!!} (A - I)^i$$

implies that

$$Q = \sqrt{A} = \sqrt{I + (A - I)} = \sum_{i=0}^{\infty} (-1)^i \frac{(2i - 3)!!}{(2i)!!} (A - I)^i.$$
where (A − I)_{jk} denotes the (j, k)th entry of A − I and similar for (A − I)^{i} \ k. It follows that

\[ |q_{jk}| \leq K |j-k|/b \]

for some constant K. This finishes the proof. \( \square \)

Let us write

\[ Q = \begin{bmatrix} \alpha_{1} & B & \alpha_{2} \\ B^{\dagger} & Q_{N} & C^{\dagger} \\ \alpha_{3} & C & \alpha_{4} \end{bmatrix} \quad \text{and} \quad A = \begin{bmatrix} \beta_{1} & a & \beta_{2} \\ a^{\dagger} & A_{N} & c^{\dagger} \\ \beta_{3} & c & \beta_{4} \end{bmatrix}. \]

Note that \( Q^{2} = A \) implies \( A_{N} = Q_{N}^{2} + B^{\dagger}B + C^{\dagger}C \) or \( \hat{Q}_{N}^{2} - Q_{N}^{2} = B^{\dagger}B + C^{\dagger}C \)

where \( \hat{Q}_{N} = A_{N}. \) Thus, we have

\[ (Q_{N} + \hat{Q}_{N})(\hat{Q}_{N} - Q_{N}) = \hat{Q}_{N}^{2} - Q_{N}^{2} + Q_{N}\hat{Q}_{N} - \hat{Q}_{N}Q_{N} = B^{\dagger}B + C^{\dagger}C + R, \quad (7) \]

where \( R \) is defined in the following,

**Lemma 3.4.** (cf. [Lai'94]) Let \( R = (r_{jk})_{-N \leq j, k \leq N} := Q_{N}\hat{Q}_{N} - \hat{Q}_{N}Q_{N}. \) Then \( r_{jk} = O(r^{-N/(4b)}) \) for \( k = -N/4 + 1, \ldots, N/4 - 1 \) and \( j = -N, \ldots, N. \)

**Proof:** (of Theorem 3.2.) From equation (6) we find that, \( (\hat{Q}_{N} - Q_{N}) = (Q_{N} + \hat{Q}_{N})^{-1}(B^{\dagger}B + C^{\dagger}C + R). \) By Lemma 3.3., we can prove that the entries of \( B^{\dagger}B + C^{\dagger}C \) have the exponential decay property: \( (B^{\dagger}B + C^{\dagger}C)_{jk} = O(r^{-|k|}), -N \leq k \leq N. \)

The positivity of \( A \) implies that \( Q \) is positive and so is \( Q_{N}. \) It follows that \( \|Q_{N}^{-1}\|_{2} \) is uniformly bounded, furthermore since \( hatQ_{N} \) ia also nonegative we find,

\[ \|(Q_{N} + \hat{Q}_{N})^{-1}\|_{2} \leq \|Q_{N}^{-1}\|_{2} \leq K_{1} < \infty \]

for a positive constant \( K_{1} \) independent of \( N, \) where we have used the fact that \( \hat{Q}_{N} \) is nonnegative. Therefore, we conclude that

\[ \|(\hat{Q}_{N} - Q_{N})\delta_{N}\|_{2} \leq \|(Q_{N} + \hat{Q}_{N})^{-1}\|(B^{\dagger}B + C^{\dagger}C + R)\delta_{N}\|_{2} \leq K_{1}\|(B^{\dagger}B + C^{\dagger}C + R)\delta_{N}\|_{2} \]

where \( \delta_{N} \) is the finite vector whose entries match those of \( \delta. \) The proof is completed by extending \( Q_{N}, \hat{Q}_{N}, \) replacing \( \delta_{N} \) by \( \delta, \) and noticing that by Lemma 3.3 \( \|(Q_{N} - Q)\delta\|_{2} < K_{1}\lambda^{N}, \lambda < 1. \) \( \square \)
Proof: (of Theorem 3.1) Suppose that

\[ \sup_{|z|=1} \| P(z) \|_2 < 1. \]  

(8)

Otherwise divide \( P \) by a sufficiently large constant so that (8) holds. Let \( Q \) be the unique positive square root of \( P \), and \( Q_N \) the positive square root of \( P_N \). From Theorem 3.2 we know that \( \|(Q_N - Q)\delta\|_2 < K\rho^N \) with \( \rho < 1 \). Let \( U \) be the unitary matrix such that \( C = UQ \). Then

\[ \|(Q_N - Q)\delta\|_2 = \|(UQ_N - C)\delta\|_2. \]

Write \( UQ_N = \tilde{Q}_N + L^1_N \) where \( \tilde{Q}_N \) is upper triangular and \( L^1_N \) is strictly lower triangular, then \( UQ_N = q_N + l_N \) where \( q_N = \Pi_N \tilde{Q}_N \Pi^1_N \) and \( l_N = L^1_N + \tilde{Q}_N - q_N \). Theorem 3.2 shows that \( \|l_N\delta\|_2 \) tends to zero exponentially fast. Furthermore since \( \tilde{Q}_N \) is symmetric,

\[ P_N = \tilde{Q}_N^2 = \tilde{Q}_N^\dagger \tilde{Q}_N = (U\tilde{Q}_N)^\dagger(U\tilde{Q}_N) \]

\[ = (q_N + l_N)^\dagger(q_N + l_N) \]

\[ = q_N^\dagger q_N + l_N^\dagger l_N + q_N^\dagger l_N + l_N^\dagger q_N. \]

That is, we have

\[ C_N^\dagger C_N - q_N^\dagger q_N = l_N^\dagger q_N + q_N^\dagger l_N + l_N^\dagger u_N. \]

Since \( Q_N \) is uniformly bounded so is \( q_N \) and we find,

\[ \|(C_N^\dagger C_N - q_N^\dagger q_N)\delta\|_2 < K_2\lambda^N. \]

Restricting the above quantities to their finite matrices we note because of the strict positivity of \( P \), \( \|C_N\|_2 \) is uniformly bounded from below hence \( C_N^{-1} \) is uniformly bounded. Furthermore since \( C_N \) has the same size as \( q_N \),

\[ \|(I - (C_N^\dagger)^{-1} q_N^\dagger q_N C_N^{-1})\delta_N\|_2 < K_3\lambda^N, \]

where \( \delta_N = C_N\delta \) for any \( \delta \) with finitely many nonzero entries. Note that the factor \( q_N C_N^{-1} \) is upper triangular while \( (C_N^\dagger)^{-1} q_N^\dagger \) is lower triangular. The above inequality shows that \( \|(q_N C_N^{-1} - I)\delta\|_2 < K_3\lambda^N \). This completes the proof. \( \Box \)

§4. Numerical Examples

In this section we give three examples to illustrate how the computational method works for polynomial matrix factorizations.

Example 4.1. We first consider a univariate polynomial matrix

\[ P(z) := \begin{bmatrix} 8 + z + 1/z & 1 + z \\ 1 + 1/z & 1 \end{bmatrix}. \]
It is clear that the matrix is Hermitian and positive definite. We write
\[
P(z) = \begin{bmatrix} 8 & 1 \\ 1 & 1 \end{bmatrix} + \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix} z + \begin{bmatrix} 1 & 0 \\ 1 & 0 \end{bmatrix} /z.
\]

We assemble a bi-infinite Toeplitz matrix whose $10 \times 10$ block is as shown below.
\[
\begin{bmatrix}
8 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 8 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 8 & 1 & 1 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 8 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 8 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1
\end{bmatrix}
\]

We use the Cholesky decomposition method to a $20 \times 20$ central block and get a lower triangular matrix $F$. Let $P_0$ be the right and bottom $2 \times 2$ block from $F$ which is
\[
P_0 := \begin{bmatrix} \sqrt{385} & 0 \\ \frac{6}{\sqrt{385}} & \frac{\sqrt{2310}}{55} \end{bmatrix}.
\]

Choose the $2 \times 2$ block next to $P_0$ as follows
\[
P_1 := \begin{bmatrix} \sqrt{385} & -\frac{\sqrt{2310}}{55} \\ \frac{55}{\sqrt{385}} & \frac{\sqrt{2310}}{385} \end{bmatrix}
\]

Define $Q^\dagger(z) = P_0 + P_1/z$ and then we have $P(z) = Q(z)^\dagger Q(z)$. □

**Example 4.2.** We next consider a bivariate polynomial
\[
P(x, y) = 41 + 5x^2 + 5y^2 + 15/x + 20/y + 5/x^2 + 5/y^2 + 15x + 20y + 5xy + 8y/x + 5/(xy) + 8x/y + 2x/y^2 + 3y/x^2 + 3x^2/y + x^2/y^2 + 2y^2/x + y^2/x^2
\]

It is a positive polynomial since $P(x, y) = p(x, y)p(1/x, 1/y)$ with $p(x, y) = 5 + 2x + 3y + xy + x^2 + y^2$. Let us write
\[
P(x, y) = [1, 1/x, 1/x^2] \tilde{P}(y) \begin{bmatrix} 1 \\ x \\ x^2 \end{bmatrix},
\]

with
\[
\tilde{P}(y) :=
\begin{bmatrix}
\frac{41}{3} + \frac{5y^2}{3} + \frac{20}{3y} + \frac{5}{3y^2} + \frac{20}{3}y \\
\frac{15}{2} + 4y + \frac{5}{2y} + y^2 \\
5 + 3y + y^2
\end{bmatrix}
\begin{bmatrix}
\frac{15}{2} + \frac{5}{2y} + y^2 \\
\frac{41}{3} + \frac{5y^2}{3} + \frac{20}{3y} + \frac{5}{3y^2} + \frac{20}{3}y \\
\frac{15}{2} + \frac{5}{2y} + y^2
\end{bmatrix}
\begin{bmatrix}
\frac{5}{3} + \frac{1}{y^2} \\
\frac{15}{2} + \frac{5}{2y} + y^2 \\
\frac{41}{3} + \frac{5y^2}{3} + \frac{20}{3y} + \frac{5}{3y^2} + \frac{20}{3}y
\end{bmatrix}.
\]
Then we can write
\[ P(x, y) = [1, 1/x, 1/x^2] \tilde{P}(y) \begin{bmatrix} 1 \\ x \\ x^2 \end{bmatrix}, \]
where \( \tilde{P}(y) = \sum_{j=-2}^{2} p_j y^j \) with \( p_{-2}, \cdots, p_2 \) being given below:
\[
p_0 = \begin{bmatrix} 41/3 & 15/2 & 5 \\ 15/2 & 41/3 & 20/3 \\ 5 & 15/2 & 41/3 \end{bmatrix}, \quad p_1 = \begin{bmatrix} 20/3 & 5/2 & 0 \\ 4 & 20/3 & 5/2 \\ 3 & 4 & 20/3 \end{bmatrix}, \quad p_{-1} = p_1^\dagger, \\
p_2 = \begin{bmatrix} 5/3 & 0 & 0 \\ 1 & 5/3 & 0 \\ 1 & 1 & 5/3 \end{bmatrix}, \quad p_{-2} = p_2^\dagger.
\]
We now assemble a bi-infinite Toeplitz matrix whose \( 9 \times 9 \) central block are shown as follows:
\[
\begin{bmatrix}
41/3 & 15/2 & 5 & 20/3 & 5/2 & 0 & 5/3 & 0 & 0 \\
15/2 & 41/3 & 15/2 & 4 & 20/3 & 5/2 & 1 & 5/3 & 0 \\
5 & 15/2 & 41/3 & 3 & 4 & 20/3 & 1 & 1 & 5/3 \\
20/3 & 4 & 3 & 41/3 & 15/2 & 5 & 20/3 & 5/2 & 0 \\
5/2 & 20/3 & 4 & 15/2 & 41/3 & 15/2 & 4 & 20/3 & 5/2 \\
0 & 5/3 & 1 & 1 & 20/3 & 4 & 3 & 41/3 & 15/2 \\
5/3 & 0 & 5 & 20/3 & 5 & 15/2 & 41/3 & 15/2 & 5 \\
0 & 0 & 5/3 & 0 & 5/2 & 20/3 & 5 & 15/2 & 41/3 \\
\end{bmatrix}
\]
We use the Cholesky factorization of a central block matrix of size \( 60 \times 60 \). Let \( F \) be the lower triangular factorization. Then choose \( Q_0 \) to be the \( 3 \times 3 \) block at the bottom and right of \( F \), \( Q_1 \) the \( 3 \times 3 \) block next to \( Q_1 \) and \( Q_2 \) the \( 3 \times 3 \) block next to \( Q_1 \) that is
\[
Q_0 = \begin{bmatrix}
3.185602126 & 0 & 0 \\
1.87365128 & 2.539725049 & 0 \\
1.524622962 & 1.128505745 & 2.269126602 \\
\end{bmatrix},
\]
\[
Q_1 = \begin{bmatrix}
1.797364251 & 0.08381502303 & -0.0003518239229 \\
0.7675275947 & 1.633796832 & 0.0615031598 \\
0.00008111923034 & 0.9665117592 & 1.856367398 \\
\end{bmatrix},
\]
\[
Q_2 = \begin{bmatrix}
0.5231873284 & 0.007768330871 & 0.08530594055 \\
0 & 0.6562390159 & 0.1143305535 \\
0 & 0 & 0.7344969935 \\
\end{bmatrix}.
\]
Let \( Q(y)^\dagger = Q_0 + Q_1/y + Q_2/y^2 \) and then \( Q(y)^\dagger Q(y) \approx \tilde{P}(y) \). In fact the maximum error of each entry of \( Q(y)^\dagger Q(y) - \tilde{P}(y) \) is less than or equal to \( 10^{-8} \). \qed
Example 4.3. Let us consider a bivariate polynomial which has a zero on the bi-torus:

\[ P(x, y) = 30 + 14/x + 11/y + 4/x/y + 14x + 6x/y + 11y + 6y/x + 4xy. \]

It is the product of \( P(x, y) = (4 + 3x + 2y + 1)(4 + 3/x + 2/y + 1) \) which is zero at \( x = -1, y = -1 \). We write

\[ P(x, y) = p_0(y) + p_1(y)x + p_{-1}(y)/x \]

for \( p_0(y) = 30 + 11/y + 11y, p_1(y) = 14 + 6y + 4/y, \) and \( p_{-1}(y) = 14 + 4y + 6/y. \) It is the symbol of an bi-infinite Toeplitz matrix. One of its central section is as shown below.

\[
\begin{bmatrix}
11/y + 30 + 11y & 4/y + 14 + 6y & 0 & 0 \\
6/y + 14 + 4y & 11/y + 30 + 11y & 4/y + 14 + 6y & 0 \\
0 & 6/y + 14 + 4y & 11/y + 30 + 11y & 4/y + 14 + 6y \\
0 & 0 & 6/y + 14 + 4y & 11/y + 30 + 11y
\end{bmatrix}.
\]

Since \( P(x, y) \) has no simple factors (see the next section), any central sections of the bi-infinite Toeplitz matrix is positive by Lemma 5.1. We consider several central sections of size \( m = 16 \times 16, 32 \times 32, 64 \times 64 \) and \( 128 \times 128 \). For each of these central sections, \( P_m \) is a univariate polynomial in \( y \) with matrix coefficients and \( P_m(y) \) is positive. Thus, \( P_m(y) = Q_m(y)^3Q_m(y) \). To compute \( Q_m(y) \), we use the computational method in §3 to yield an approximation \( \tilde{Q}_m \) of \( Q_m \). As the size of central sections increases, the \( Q_m \) converges to the corresponding entries in the bi-infinite Toeplitz matrix. We use the entries on the last row of \( \tilde{Q}_m \) to construct an approximation of \( Q_m(y) \) and hence the factorization of \( P(x, y) \) and listed below.

\[
\begin{array}{c|c}
\text{size} & \text{factorization} \\
16 \times 16 & 4.01207952 + 2.984741799x + 2.000226870y + 0.996712925xy \\
32 \times 32 & 4.004041536 + 2.994924757x + 2.000034879y + 0.998949058xy \\
64 \times 64 & 4.001381387 + 2.998269650x + 2.000005690y + 0.999648058xy \\
128 \times 128 & 4.000693699 + 2.999134582x + 1.99999896y + 0.999821915xy
\end{array}
\]

As we know that the factorization is \( 4 + 3x + 2y + 1 \), the approximations are very good. □

§5. Nonegative bivariate Trignometric Polynomials

Finally we consider the problem of factorization of nonnegative multivariate polynomials. Let us start with \( P(z, w) \geq 0 \). If for some \( z_0 \) with \( |z_0| = 1 \), \( P(z_0, w) = 0 \) for all \( w \) with \( |w| = 1 \), we say that \( P(z, w) \) has a simple factor at \( z_0 \). If \( P(z, w) \) has a simple factor at \( z_0 \), then \( P(z, w) \) has factors \( (z - z_0) \) and \( (1/z - 1/z_0) \). Let us factor them out. Then \( P(z, w)/((z-z_0)(1/z-1/z_0)) \) is still nonnegative. Similarly, if \( P(z, w_0) = 0 \) for all \( z \) with \( |z| = 1 \), \( P(z, w) \) has a simple factor at \( w_0 \). In this
case, $P(z, w)$ has two factors $(w - w_0)$ and $(1/w - 1/w_0)$ which can be factored out from $P(z, w)$. Without loss of generality, we may assume that $P(z, w) \geq 0$ does not have any simple factors. Writing $P(z, w) = \sum_{j=-n}^{n} p_j(w)z^j$, we view that $P(z, w)$ is a polynomial of $z$ and it is the symbol of a bi-infinite Toeplitz matrix in (4) with $w$ in place of $z_2$. We have the following

**Lemma 5.1.** Suppose that $P(z, w) \geq 0$ does not have any simple factors. Then any central section of the bi-infinite Toeplitz matrix in (4) is strictly positive definite.

**Proof:** Since $P(z, w) \geq 0$, we know that any central section of the matrix in (4) is nonnegative definite. Suppose that a central section $T_m(w)$ of the matrix in (4) is not positive definite for $w = w_0$. Then there exists a vector $x$ such that $T_m(w_0)x = 0$, i.e., $x^\dagger T_m(w_0)x = 0$. Thus, we have, for $z = e^{i\theta}$,

$$0 = x^\dagger T_m(w_0)x = \frac{1}{2\pi} \int_{0}^{2\pi} F(x)^* P(z, w_0) F(x) d\theta.$$ 

It follows that

$$|F(x)|^2 P(z, w_0) = 0,$$

and hence, $P(z, w_0) \equiv 0$ since $|F(x)| \neq 0$, a.e. and $P(z, w_0)$ is a Laurent polynomial. That is, $P(z, w)$ has a simple factor at $w_0$. This contradicts the assumption on $P(z, w)$. \square

Thus, for a central section $P_m$ of size $m \times m$ in the matrix in (4), $P_m$ is positive. Since $P_m$ is a matrix polynomial in $w$, by the matrix Féjer-Riesz factorization theorem (cf. [Helson’64]), $P_m$ can be factorized into $Q_m$, i.e., $P_m(w) = Q_m(w)^* Q_m(w)$. Intuitively, the polynomial $Q_m$ is a good approximation of the factorization of the bi-infinite Toeplitz matrix $P$ in (4) as $m$ sufficiently large. In the previous section, we presented an example (Example 4.3.) of $P(z, w)$ which is nonnegative without simple factors. Using our symbol approximation method, we compute an approximation of the factorization of $P_m$ for $m = 16, 32, 64,$ and 128. The numerical computation shows the factorizations converge.

Let us now discuss the convergence a little bit more in detail. For simplicity, let $A$ be a bi-infinite Toeplitz matrix associated with a univariate Laurent polynomial $A(z)$ and $A_N = (a_{jk})_{-N \leq j, k \leq N}$ be a central section of size $(2N + 1) \times (2N + 1)$ for a positive integer $N$. Suppose that each $A_N$ is strictly positive. Thus we can obtain a factorization $A_N = B_N^* B_N$ by Cholesky factorization.

**Lemma 5.2.** For any $x, y \in \ell_2$, $x_N^\dagger A_N y := x_N^\dagger A_N y_N$ converges to $x^\dagger A y$ as $N \rightarrow +\infty$, where $x_N = (x_{-N}, \cdots, x_0, \cdots, x_N)^\dagger$ is the central section of size $2N + 1$ of $x$ around the index 0 and similar for $y_N$. 

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Proof: For an integer $N > 0$,

$$x^\dagger A_N y - x^\dagger A y = \frac{1}{2\pi} \int_0^{2\pi} (F(x_N)^* A(z) F(y_N) - F(x)^* A(z) F(y)) d\theta$$

$$= \frac{1}{2\pi} \int_0^{2\pi} (F(x_N) - F(x))^* A(z) F(y_N) d\theta$$

$$+ \frac{1}{2\pi} \int_0^{2\pi} F(x)^* A(z) (F(y_N) - F(y)) d\theta$$

where $z = e^{i\theta}$. In the first inequality we used the fact that $x^\dagger A_N x = (\Pi_N x)^\dagger A \Pi_N x$ where $\Pi_N$ is the projection defined in section 3. Thus

$$|x^\dagger A_N y - x^\dagger A y|$$

$$\leq \|x - x_N\|_2 \|A(z)\|_\infty \|y\|_2 + \|y - y_N\|_2 \|A(z)\|_\infty \|x\|_2$$

$$\rightarrow 0$$

as $N \rightarrow +\infty$. Here, $\|A(z)\|_\infty$ denotes the maximum norm of $A(z)$ over the circle $|z| = 1$. This completes the proof.

A consequence of the above Lemma 5.2 is that $\|B_N x\|_2^2$ converges to $x^\dagger A x$. If $A$ can be factored to $A = B^\dagger B$. Then $\|B_N x\|_2 \rightarrow \|Bx\|_2$. The following is another consequence of Lemma 5.2.

**Lemma 5.3.** Let $B_N$ be a factorization of $A_N$, i.e., $A_N = B_N^\dagger B_N$. Then $\|B_N\|$ is bounded independent of $N$. 

**Proof:** By Lemma 5.2, there exists a constant $C$ such that for $N$ large enough,

$$\|B_N x\|_2^2 = x^\dagger A_N x \leq x^\dagger A x + C = \|x\|_2^2 \|A(z)\|_\infty + C.$$

Hence, $\|B_N\| := \max_{\|x\|_2 = 1} \|B_N x\|_2$ is bounded.

Note that all $B_N$ are banded upper triangular matrices with one half the band width as that of $A$. Thus, each row (or column) of $B_N$ has finitely many nonzero entries. Lemma 5.3 implies that each row (or column) of $B_N$ is bounded in $\ell_2$ norm and hence each entry in any row is bounded. Therefore there exists a subsequence of $B_{N_j}$ such that each entry with indices $(j, k)$ in $B_{N_i}$ converges as $i \rightarrow +\infty$. That is, for any vector $x = (x_i)_{i \in \mathbb{Z}} \in \ell_2$ with finitely many nonzero entries $x_i$’s, we have

$$B_{N_i} x \rightarrow B x.$$

for a bi-infinite matrix $B$. By Lemma 5.2 again, we have $x^\dagger B^\dagger B y = x^\dagger A y$ for all vectors $x$ and $y$ with finitely many nonzero entries. However since these are dense in $\ell_2$ we find $B^\dagger B = A$. Note that $B$ is an upper triangular matrix with the half the band width as that of $A$. If $B$ is a Toeplitz matrix, we immediately know that $A(z)$ has a factorization such that $A(z) = B(z)^* B(z)$. Therefore, we end with
Theorem 5.4. Let $P(z, w)$ be a nonnegative Laurent polynomial with no simple zeros. Let $\mathcal{P}$ be a bi-infinite Toeplitz matrix with Laurent polynomial entries in $w$, $P_N$ be the central section as described above and $B_N$ be its upper triangular Cholesky factor. Then there is a subsequence of $B_N$ convergent to $B$ entrywise, where $\mathcal{P} = B^\dagger B$. If $B$ is Block Toeplitz, then $P(z, w)$ can be factored into a sum of square magnitudes of finitely many polynomials in $z$ and $w$.

Theorem 5.4 provides a computational method to check if a nonnegative Laurent polynomial $P(z, w)$ can be factorized. That is, we compute Cholesky factorization of central sections of the bi-infinite Toeplitz matrix $\mathcal{P}$ associated with $P(z, w)$ and observe if the factorization matrices converge to a Toeplitz matrix or not. If they converge, $P(z, w)$ has a factorization.

§6. Remarks

1. It is interesting to point out that the symbol approximation method discussed in [Lai’94] is very much like the Bauer method invented in 1955 (see [Sayed and Kailath’01] and its references). A slight difference is that the singular value decomposition (SVD) instead of the Cholesky decomposition is used to factorize the matrices associated with Laurent polynomial $P(z) \geq 0$.

2. When $P(z)$ is a matrix polynomial in the univariate setting [Hardin, Hogan and Sun’04] have demonstrated a constructive method to factor $P(z) = Q(z)^\dagger Q(z)$ when $P(z)$ has a nonzero monomial determinant.

3. When $P(z)$ is a matrix polynomial in the univariate setting [Youla and Kazanjian’78] used a Bauer type method to compute the factorization of $P(z)$. They showed that the solution obtained from the Bauer type method converges to the factorization under a weaker condition that

$$\frac{1}{2\pi} \int_{-\pi}^{\pi} \log \det P(z) d\theta > -\infty$$

than the positivity condition of $P(z)$. In our Theorem 3.1. we showed the exponential convergence of the method which greatly improves their convergence analysis.

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