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EXPLICIT REPRESENTATION OF FINITE PREDICTOR COEFFICIENTS AND ITS APPLICATIONS

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(SHORT TITLE: FINITE PREDICTOR COEFFICIENTS)

Abstract. We consider the finite-past predictor coefficients of stationary time series, and establish an explicit representation for them, in terms of the MA and AR coefficients. The proof is based on the alternate applications of projection operators associated with the infinite past and the infinite future. Applying the result to long memory processes, we give the rate of convergence of the finite predictor coefficients and prove an inequality of Baxter-type.

1. Introduction

Let \( \{X_k\} = \{X_k : k \in \mathbb{Z}\} \) be a real, zero-mean, weakly stationary process, defined on a probability space \((\Omega, \mathcal{F}, P)\), which we shall simply call a stationary process. We denote by \(H\) the real Hilbert space spanned by \(\{X_k : k \in \mathbb{Z}\}\) in \(L^2(\Omega, \mathcal{F}, P)\). The norm of \(H\) is given by \(\|Y\| := E[Y^2]^{1/2}\). For \(n \in \mathbb{N}\), we denote by \(H[-n,-1]\) and \(H(-\infty,-1]\) the subspaces of \(H\) spanned by \(\{X_{-n}, \ldots, X_{-1}\}\) and \(\{X_k : k \leq -1\}\), respectively. We write \(P[-n,-1]\) and \(P(-\infty,-1]\) for the orthogonal projection operators of \(H\) onto \(H[-n,-1]\) and \(H(-\infty,-1]\), respectively. The projection \(P[-n,-1]X_0\) (respectively, \(P(-\infty,-1]\)X_0) stands for the best linear predictor of the future value \(X_0\) based on the finite past \(\{X_{-n}, \ldots, X_{-1}\}\) (respectively, the infinite past \(\{X_k : k \leq -1\}\)), and its mean square prediction error is given by \(\sigma_n^2 := \|X_0 - P[-n,-1]X_0\|^2\) (respectively, \(\sigma^2 := \|X_0 - P(-\infty,-1]\)X_0\|^2\).

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For nondeterministic \( \{X_k\} \) (see Section 2.1), the finite predictor coefficients \( \phi_{n,j} \) are the uniquely determined ones in

\[
P_{[-n,-1]}X_0 = \sum_{j=1}^{n} \phi_{n,j} X_{-j}.
\]

As is well known, we can calculate the numerical values of \( \phi_{n,1}, \ldots, \phi_{n,n} \) as well as the mean square prediction error \( \sigma_n^2 \) from the values \( \gamma(0), \ldots, \gamma(n) \) of the autocovariance function of \( \{X_k\} \), using recursive algorithms such as the Durbin–Levinson algorithm [see, e.g., Section 5.2 in Brockwell and Davis (1991)]. The recursive methods are of great practical importance in time series analysis. However, they are not necessarily effective in problems of theoretical character, in particular, those related to the asymptotic behavior as \( n \to \infty \).

A classical problem of this type is the rate of convergence of \( \sigma_n^2 - \sigma^2 \downarrow 0 \) as \( n \to \infty \). See, e.g., Ginovian (1999), where references to earlier work — by Grenander and Rosenblatt, Grenander and Szegő, Baxter, Ibragimov and many others — are given. The arguments in these references are closely related to the theory of orthogonal polynomials as described in Grenander and Szegő (1958) and Simon (2005a, 2005b).

A new approach to a related problem was introduced by Inoue (2000). For the partial autocorrelation coefficients \( \alpha(n) = \phi_{n,n} \) of a stationary process \( \{X_k\} \) with short or long memory, the asymptotic behavior of \( |\alpha(n)| \) as \( n \to \infty \) was obtained using a representation of the mean square prediction error \( \sigma_n^2 \) in terms of the MA (moving-average) coefficients \( c_k \) and the AR (autoregressive) coefficients \( a_k \) (see Section 2.2 for the definitions of \( c_k \) and \( a_k \)). By the same approach but with extra complication, similar results on \( |\alpha(n)| \) were obtained in Inoue (2002) and Inoue and Kasahara (2004) for the fractional ARIMA (autoregressive integrated moving-average) processes. The fractional ARIMA model is an important parametric model including a class of long memory processes. It was independently introduced by Granger and Joyeux (1980) and Hosking (1981) (see Example 2.6). The advantage of such approach, i.e., that via \( c_k \) and \( a_k \), has become more apparent in Inoue (2001) where a representation of the partial autocorrelation function \( \alpha(\cdot) \) itself, in terms of \( c_k \) and \( a_k \), was derived. The representation enabled us to study the behavior of \( \alpha(\cdot) \) more directly, and thereby to improve results in several ways. In particular, the asymptotic behavior of \( \alpha(n) \) as \( n \to \infty \), rather than that of \( |\alpha(n)| \), was obtained.

In this paper, our main interest is in the finite predictor coefficients \( \phi_{n,j} \) which are among the most basic quantities in the prediction theory for \( \{X_k\} \). After we
establish an explicit representation of the type above for \( \phi_{n,j} \), i.e., that in terms of the MA coefficients \( c_k \) and the AR coefficients \( a_k \), we provide two applications of the representation to long memory processes.

For \( n \in \mathbb{N} \), we write \( H_{[-n,\infty]} \) for the subspace of \( H \) spanned by \( \{X_k : k \geq -n\} \), and \( P_{[-n,\infty]} \) for the orthogonal projection operator of \( H \) onto \( H_{[-n,\infty]} \). To prove the representation of \( \phi_{n,j} \), we use an approximation scheme based on the alternate applications of the projections \( P_{(-\infty,-1]} \) and \( P_{[-n,\infty]} \). In so doing, the following equalities play a key role:

\[
H_{(-\infty,-1]} \cap H_{[-n,\infty]} = H_{[-n,-1]}, \quad n = 1, 2, \ldots
\]

(see Theorem 2.2). For example, it is known that (1.2) holds if \( \{X_n\} \) is purely nondeterministic and has spectral density \( \Delta(\cdot) \) such that

\[
\int_{-\pi}^{\pi} \frac{1}{\Delta(\lambda)} d\lambda < \infty
\]

[Theorem 3.1 in Inoue (2000)]. We discuss the equivalence between (1.2) and complete nondeterminism (see Theorem 2.3 and Remark 2).

When Wiener’s prediction formula (1.4) below is available, we thus obtain a representation of \( \phi_{n,j} \) in terms of \( c_k \) and \( a_k \) (Theorem 2.5). However, in applications, it is essential that \( \phi_{n,j} \) is expressed in terms of absolutely convergent series made up of \( c_k \) and \( a_k \). We derive such an expression (Theorem 2.9) under additional conditions on \( c_k \) and \( a_k \), that is, (A1) or (A2) in Section 2.3. The condition (A1) corresponds to short memory processes, while (A2) to long memory processes.

The first application of the representation of \( \phi_{n,j} \) concerns the rate of convergence of \( \phi_{n,j} \) toward its limit as \( n \to \infty \). Under suitable conditions, \( \phi_{n,j} \) converges to the infinite predictor coefficient \( \phi_j \) in

\[
P_{(-\infty,-1]} X_0 = \sum_{j=1}^{\infty} \phi_j X_{-j}.
\]

(1.4)

The rate at which \( \phi_{n,j} \) converges to \( \phi_j \) is a fundamental problem in prediction theory and time series analysis. A textbook treatment of this problem can be found in Pourahmadi [(2001), Section 7.6]. Using the representation of \( \phi_{n,j} \), we show that

\[
\phi_{n,j} - \phi_j = \sum_{k=2}^{\infty} g_k(n,j),
\]

where \( g_k(n,j) \) is a function of \( \{c_k\} \) and \( \{a_k\} \) (see (2.28)), and we examine the convergence rate for a long memory process whose autocovariance function \( \gamma(\cdot) \) is regularly varying at infinity with index \( -p \) for some \( p \in (0,1) \). It is shown that
\[
\lim_{n \to \infty} n\{\phi_{n,j} - \phi_j\} \text{ exists, and the limit is calculated exactly in terms of } p \text{ and } \{\phi_k\} \text{ (Theorem 3.3). It is interesting that the rate of convergence does not depend on } p.
\]

The second application of the representation of \(\phi_{n,j}\) is related to the additional error \(\|P_{[-n,-1]}X_0 - \sum_{j=1}^{n} \phi_j X_{-j}\|\) that arises when we use the infinite predictor coefficients \(\phi_j\) instead of the finite ones \(\phi_{n,j}\). There exists a known inequality that deals with this problem, and is commonly referred to as Baxter’s inequality [see Baxter (1962); see also Berk (1974), Cheng and Pourahmadi (1993) and Section 7.6.2 in Pourahmadi (2001)]. It takes the form

\[
(1.5) \quad \sum_{j=1}^{n} |\phi_{n,j} - \phi_j| \leq M \sum_{k=n+1}^{\infty} |\phi_k|
\]

with finite positive constant \(M\). The original inequality (1.5) of Baxter was an assertion for short memory processes. By simple arguments based on the representation of \(\phi_{n,j}\), we prove (1.5) for long memory processes including the fractional ARIMA processes (Theorem 4.1).

In Section 2, we prove the representation of the finite predictor coefficients \(\phi_{n,j}\). In Section 3, we apply it to show the rate of convergence of \(\phi_{n,j}\) for long memory processes. In Section 4, we apply the representation to prove an inequality of Baxter-type for long memory processes.

2. FINITE PREDICTOR COEFFICIENTS

Let \(\{X_n\} = \{X_n : n \in \mathbb{Z}\}\) be a stationary process; as stated in Section 1, this means that \(\{X_n\}\) is a real, zero-mean, weakly stationary process, defined on a probability space \((\Omega, \mathcal{F}, P)\). The autocovariance function \(\gamma(\cdot)\) of \(\{X_n\}\) is defined by

\[
\gamma(n) := E[X_nX_0], \quad n \in \mathbb{Z}.
\]

As we also stated in Section 1, we denote by \(H\) the closed real linear hull of \(\{X_k : k \in \mathbb{Z}\}\) with respect to the norm \(\|Y\| := E[|Y|^2]^{1/2}\). Then \(H\) is a real Hilbert space with inner product \((Y,Z) := E[YZ]\). For \(n, m \in \mathbb{Z}\) with \(n \leq m\), we write \(H_{(-\infty,n]}\), \(H_{[n,\infty)}\), \(H_{[n,m]}\) and \(H_{(n)}\) for the closed subspaces of \(H\) spanned by \(\{X_k : -\infty < k \leq n\}\), \(\{X_k : n \leq k < \infty\}\), \(\{X_k : n \leq k \leq m\}\), and \(X_n\), respectively. Notice that \(H_{(n)} = H_{[n,n]}\). For an interval \(I\), we write \(P_I\) for the orthogonal projection operator of \(H\) onto \(H_I\).
A stationary process \( \{X_n\} \) is said to be purely nondeterministic (PND) if
\[
\bigcap_{n=-\infty}^{\infty} H_{(-\infty,n]} = \{0\}.
\]
If there exists an even, nonnegative, and integrable function \( \Delta(\cdot) \) on \([-\pi,\pi]\) such that
\[
\gamma(n) = \int_{-\pi}^{\pi} e^{in\lambda} \Delta(\lambda) d\lambda, \quad n \in \mathbb{Z},
\]
then \( \Delta(\cdot) \) is called a spectral density of \( \{X_n\} \). As is well known, \( \{X_n\} \) is PND if and only if it has a positive spectral density such that
\[
\int_{-\pi}^{\pi} |\log \Delta(\lambda)| d\lambda < \infty \quad \text{[see, e.g., Chapter II in Rozanov (1967)].}
\]

2.1. Convergence of an approximation scheme. Let \( Y \in H \). If \( \{X_k\} \) is nondeterministic, that is, \( X_0 \not\in H_{(-\infty,1]} \), then \( X_{-n}, \ldots, X_{-1} \) are linearly independent, whence we can express the predictor \( P_{[-n,1]}Y \) uniquely in the form
\[
P_{[-n,1]}Y = \sum_{j=1}^{n} \phi_{n,j}(Y) X_{-j}.
\]
(2.1)

In this section, we prove the convergence of an approximation scheme for computing the real coefficients \( \phi_{n,j}(Y) \).

For \( n, k \in \mathbb{N} \), we define the orthogonal projection operator \( P_n^k \) by
\[
P_n^k := \begin{cases} P_{(-\infty,-1]}, & k = 1, 3, 5, \ldots, \\ P_{[-n,\infty)}, & k = 2, 4, 6, \ldots. \end{cases}
\]
(2.2)

It should be noticed that \( \{P_n^k : k = 1, 2, \ldots\} \) is merely an alternating sequence of projection operators, first to the subspace \( H_{(-\infty,1]} \), then to \( H_{[-n,\infty)} \), and so on.

Lemma 2.1. Assume that \( \{X_n\} \) is nondeterministic. Let \( Y \) be an arbitrary element of \( H \). Then, for \( n, k \in \mathbb{N} \), there exist unique real coefficients \( \phi_{n,1}^k(Y) \), \( \ldots \), \( \phi_{n,n}^k(Y) \) as well as \( Z_n^k \in H_{(-\infty,1]} \) for \( k \) odd and \( Z_n^k \in H_{[0,\infty)} \) for \( k \) even, such that
\[
P_n^k P_{n-1}^k \cdots P_1^k Y = \sum_{j=1}^{n} \phi_{n,j}^k(Y) X_{-j} + Z_n^k.
\]

Proof. We assume that \( k \) is odd. From Lemma 5.1 in Pourahmadi (2001) (Regression Lemma), it follows that
\[
H_{(-\infty,1]} = H_{(-\infty,1]} + H_{[-n,1]} \quad \text{(direct sum)}
\]
[see the proof of Theorem 6.3 in Pourahmadi (2001)]. Since \( X_{-n}, \ldots, X_{-1} \) are linearly independent and \( P_n^k P_{n-1}^k \cdots P_1^k Y \in H_{(-\infty,1]} \), the lemma for \( k \) odd follows.

The case in which \( k \) is even is proved in a similar fashion.
It is natural to ask if $\phi_{n,j}^k(Y)$ converges to $\phi_{n,j}(Y)$ as $k \to \infty$.

**Theorem 2.2.** We assume that 

\begin{equation}
\{X_n\} \text{ is nondeterministic and satisfies (1.2).}
\end{equation}

Then, we have 

\begin{equation}
\phi_{n,j}(Y) = \lim_{k \to \infty} \phi_{n,j}^k(Y), \quad Y \in H, \ n \in \mathbb{N}, \ j = 1, \ldots, n.
\end{equation}

In particular, (2.5) holds if 

\begin{equation}
\{X_n\} \text{ is purely nondeterministic and satisfies (1.3).}
\end{equation}

**Proof.** The condition (1.2) and von Neumann’s alternating projection theorem [see, e.g., Theorem 9.20 in Pourahmadi (2001)] yield 

\begin{equation}
\text{s-lim}_{k \to \infty} P_n^k P_{n-1}^k \cdots P_1^k Y = P_{\{-n,-1\}}^n Y, \quad n = 1, 2, \ldots.
\end{equation}

We put 

\begin{equation}
\epsilon_k := X_k - P_{\{-\infty,k-1\}} X_k \quad (k \in \mathbb{Z}).
\end{equation}

Then, from Lemma 2.1, we see that 

\begin{equation}
(P_n^{2k+1} P_n^{2k} \cdots P_1^k Y, \epsilon_1, \epsilon_2, \ldots) = \phi_{n,1}^{2k+1}(Y) \cdot \|\epsilon_1\|^2.
\end{equation}

By (2.7), the left-hand side tends to $(P_{\{-n,-1\}} Y, \epsilon_1)$ as $k \to \infty$. Thus $a_{n,1} := \lim_{k \to \infty} \phi_{n,1}^{2k+1}(Y)$ exists. In the same way, letting $k \to \infty$ in 

\begin{equation}
(P_n^{2k+1} P_n^{2k} \cdots P_1^k Y, \epsilon_1, \epsilon_2) = \phi_{n,2}^{2k+1}(Y) \cdot \|\epsilon_1\|^2 + \phi_{n,1}^{2k+1}(Y) \cdot (X_1, \epsilon_2),
\end{equation}

we find the existence of $a_{n,2} := \lim_{k \to \infty} \phi_{n,2}^{2k+1}(Y)$. Repeating this argument, we see that $a_{n,j} := \lim_{k \to \infty} \phi_{n,j}^{2k+1}(Y)$ exists for all $j = 1, \ldots, n$. Hence $Z_n := \lim_{k \to \infty} Z_n^{2k+1}$ also exists in $H$, and we have 

\begin{equation}
Z_n = P_{\{-n,-1\}} Y - \sum_{j=1}^n a_{n,j} X_j.
\end{equation}

Since the right-hand side is in $H_{\{-n,-1\}}$, so is $Z_n$. Moreover, $Z_n \in H_{\{-\infty,-n-1\}}$ since, for every $k \geq 1$, $Z_n^{2k+1}$ belongs to the closed subspace $H_{\{-\infty,-n-1\}}$. Combining, $Z_n \in H_{\{-n,-1\}} \cap H_{\{-\infty,-n-1\}}$. However, by (2.3), this implies $Z_n = 0$. Thus $P_{\{-n,-1\}} Y = \sum_{j=1}^n a_{n,j} X_j$. By uniqueness, we obtain $\phi_{n,j}(Y) = a_{n,j} = \lim_{k \to \infty} \phi_{n,j}^{2k+1}(Y)$. Similarly, we have $\phi_{n,j}(Y) = \lim_{k \to \infty} \phi_{n,j}^{2k+1}(Y)$. Thus (2.5) follows. Finally, by Theorem 3.1 in Inoue (2000), (2.6) implies (2.4), whence (2.5).
Remark 1. A stationary process \( \{X_n\} \) is said to be minimal if \( X_0 \) does not belong to the closed linear span of \( \{X_k : k \in \mathbb{Z}, k \neq 0\} \) in \( H \). By Theorem 24 in Kolmogorov (1941), (2.6) is equivalent to saying that \( \{X_n\} \) is purely nondeterministic and minimal. The condition (2.6) is also equivalent to another property called pure minimality [see Makagon and Weron (1976), Salehi (1979) and Theorem 8.10 in Pourahmadi (2001)]. The condition (2.6) holds in most interesting examples, and we can easily check it.

Since the assumption (2.4) is a key to our arguments, we are interested in its characterization. The next theorem gives such a result.

**Theorem 2.3.** The condition (2.4) is equivalent to

\[
H(-\infty, -1) \cap H[0, \infty) = \{0\}.
\]

**Proof.** First we assume (2.4). Then

\[
H(-\infty, -1) \cap H[0, \infty) \subset H(-\infty, -1) \cap H[-1, \infty) = H(-1),
\]

\[
H(-\infty, -1) \cap H[0, \infty) \subset H(-\infty, 0) \cap H[0, \infty) = H(0),
\]

while \( X_{-1} \) and \( X_0 \) are linearly independent since \( \{X_n\} \) is nondeterministic. Thus (2.9) follows.

Next we assume (2.9). By the arguments in Helson and Sarason [(1967), page 6], we see that \( \{X_n\} \) is PND, whence, in particular, nondeterministic. Let \( n \in \mathbb{N} \) and \( X \in H(-\infty, -1] \cap H[-n, \infty) \). By Regression Lemma, \( X \) has a decomposition \( X = Y + Z \) with \( Y \in H(-\infty, -n-1] \) and \( Z \in H[-n, -1] \). Then \( Y = X - Z \in H(-\infty, -n-1] \cap H[-n, -1) \). However, (2.9) implies \( H(-\infty, -n-1] \cap H[-n, \infty) = \{0\} \), so that \( Y = 0 \) or \( X = Z \in H[-n, -1] \). Thus \( H(-\infty, -1] \cap H[-n, \infty) \subset H[-n, -1] \). Since the converse implication \( \supset \) is trivial, we obtain (1.2), whence (2.4).

A stationary process \( \{X_n\} \) is said to be completely nondeterministic if (2.9) holds. Thus Theorem 2.3 asserts the equivalence between (2.4) and the complete nondeterminism of \( \{X_n\} \). Complete nondeterminism was introduced by Sarason (1978).

**Remark 2.** In the first version of the manuscript, we raised the characterization of (2.4) in terms of the spectral density \( \Delta(\cdot) \) as an open problem after remarking that (2.4) implies (2.9), whence that \( \{X_n\} \) is PND. In Summer 2004, Mohsen Pourahmadi, and then an anonymous referee, suggested the equivalence between
(2.4) and (2.9), and both cited Bloomfield, Jewell and Hayashi (1983), in which several characterizations of complete nondeterminism (2.9), in terms of the outer function determined by \( \Delta(\cdot) \) which is essentially the same as \( h(z) \) in (2.11) below, are given. Thus we owe much of Theorem 2.3 to them.

2.2. Representation in terms of MA and AR coefficients. In this section, we assume that the stationary process \( \{X_n\} \) is purely nondeterministic. For \( n \in \mathbb{N} \) and \( m \in \mathbb{N} \cup \{0\} \), we can express the \((m+1)\)-step predictor \( P_{[-n,-1]}X_m \) uniquely in the form

\[
P_{[-n,-1]}X_m = \sum_{j=1}^{n} \phi_{n,j}^m X_{-j}.
\]

We are concerned with representation of the real coefficients \( \phi_{n,j}^m \), which we call the \((m+1)\)-step finite predictor coefficients. In the 1-step case \( m = 0 \), we have \( \phi_{n,j}^0 = \phi_{n,j} \) by (1.1).

We consider the following outer function:

\[
h(z) := \sqrt{2\pi} \exp \left\{ \frac{1}{4\pi} \int_{-\pi}^{\pi} \frac{e^{i\lambda} + z}{e^{i\lambda} - z} \log \Delta(\lambda) d\lambda \right\}, \quad z \in \mathbb{C}, \ |z| < 1.
\]

The function \( h(z) \) is holomorphic and has no zeros in \( |z| < 1 \), and it satisfies 
\( 2\pi \Delta(\lambda) = |h(e^{i\lambda})|^2 \) a.e., where \( h(e^{i\lambda}) := \lim_{r \uparrow 1} h(re^{i\lambda}) \). We define the MA coefficients \( c_n \) by

\[
h(z) = \sum_{n=0}^{\infty} c_n z^n, \quad |z| < 1,
\]

and the AR coefficients \( a_n \) by

\[-1/h(z) = \sum_{n=0}^{\infty} a_n z^n, \quad |z| < 1\]

[see Section 2 in Inoue (2000)]. Both \( \{c_n\} \) and \( \{a_n\} \) are real sequences, and we have \( c_0 > 0 \) and \( \sum_{n=0}^{\infty} (c_n)^2 < \infty \). The coefficients \( c_n \) and \( a_n \) are actually those that appear in the following MA(\( \infty \)) and AR(\( \infty \)) representations, respectively, of \( \{X_n\} \) (under suitable condition such as (2.15) below for the latter):

\[
X_n = \sum_{j=-\infty}^{n} c_{n-j} \xi_j, \quad n \in \mathbb{Z},
\]

\[
\sum_{j=-\infty}^{n} a_{n-j} X_j + \xi_n = 0, \quad n \in \mathbb{Z},
\]

where \( \{\xi_k\} \) is the innovation process given by \( \xi_k = \epsilon_k/\|\epsilon_k\| \) with \( \epsilon_k \) in (2.8); see, e.g., Chapter II in Rozanov (1967) for (2.12), and (4.9) in Inoue (2000) for (2.13). By the assumption that \( \{X_k\} \) is PND, \( \{\xi_k\} \) forms a complete orthonormal system of \( H \) such that, for every \( n \in \mathbb{Z} \), the closed linear span of \( \{\xi_k : -\infty < k \leq n\} \) in \( H \)
is equal to \( H_{(-\infty, n]} \). Notice that the sums in (2.13) may not converge in norm in \( H \).

**Example 2.4.** Let \( r \in (-1, 1) \). We consider the unique *causal* solution \( X_n = \sum_{j=-\infty}^{n} r^{n-j} e_j \) to the AR(1) equation \( X_n = rX_{n-1} + e_n \), where \( \{e_n : n \in \mathbb{Z}\} \) is a white noise, i.e., a sequence in \( H \) such that \( (e_n, e_m) = \delta_{nm} \) [see, e.g., Section 4.1.1 in Pourahmadi (2001)]. By standard computations, we find the following equalities:

\[
\xi_n = e_n, \quad \gamma(n) = \frac{r^{|n|}}{1 - r^2}, \quad \Delta(\lambda) = \frac{1}{2\pi} \frac{1}{|1 - re^{i\lambda}|^2}, \quad h(z) = \frac{1}{1 - rz}.
\]

\( c_n = r^n \quad (n \geq 0), \quad a_0 = -1, \quad a_1 = r, \quad a_n = 0 \quad (n \geq 2). \)

We put

\[
b_{j}^{m} := \sum_{k=0}^{m} c_k a_{j+m-k}, \quad m, j \in \mathbb{N} \cup \{0\}.
\]

In particular, \( b_{j}^{0} = c_{0} a_{j} \). For \( n \in \mathbb{N} \) and \( m, j \in \mathbb{N} \cup \{0\} \), we define \( b_{k}^{m}(n, j) \) recursively by

\[
\begin{cases}
    b_{1}^{m}(n, j) = b_{j}^{m}, \\
    b_{k+1}^{m}(n, j) = \sum_{m_1=0}^{\infty} b_{n+1}^{m_1} b_{k}^{m_1}(n, j), \quad k = 1, 2, \ldots
\end{cases}
\]  

From the proof of Theorem 2.5 below, we see that, under the condition

\[
\sum_{n=0}^{\infty} |a_n| < \infty
\]

which ensures the absolute convergence of the sums in (2.13), the sums in (2.14) also converge absolutely. We put, for \( m \in \mathbb{N} \cup \{0\} \), \( n \in \mathbb{N} \), and \( j = 1, 2, \ldots, n \),

\[
g_{k}^{m}(n, j) := \begin{cases} 
    b_{k}^{0}(n, j), & k = 1, 3, \ldots, \\
    b_{k}^{m}(n, n + 1 - j), & k = 2, 4, \ldots
\end{cases}
\]

We write \( \sum_{n=0}^{\infty} \) for the improper sum: \( \sum_{n=0}^{\infty} = \lim_{M \to \infty} \sum_{n=0}^{M} \). The following theorem gives an explicit representation of the \((m + 1)\)-step finite predictor coefficients \( \phi_{m,n} \) in (2.10), in terms of the MA and AR coefficients, under the absolute convergence of the sums in (2.13).

**Theorem 2.5.** We assume that the AR coefficients \( a_n \) of a purely nondeterministic stationary process \( \{X_n\} \) satisfy (2.15). Then we have \( \phi_{m,n} = \sum_{k=1}^{\infty} g_{k}^{m}(n, j) \) for \( n \in \mathbb{N}, \ m \in \mathbb{N} \cup \{0\} \) and \( j = 1, \ldots, n \), that is,

\[
P_{[-n, -1]} X_{m} = \sum_{j=1}^{n} \left\{ \sum_{k=1}^{\infty} g_{k}^{m}(n, j) \right\} X_{-j}.
\]
Proof. For $m \in \mathbb{N} \cup \{0\}$ and $n \in \mathbb{N}$, we have the following Wiener prediction formulas [see, e.g., Theorem 4.4 in Inoue (2000)]:

\begin{align}
(2.16) \quad P_{[-\infty,-1]}X_m &= \sum_{j=1}^{\infty} b_j^m X_{-j}, \\
(2.17) \quad P_{[-n,-\infty)}X_{-n-1-m} &= \sum_{j=1}^{\infty} b_j^m X_{-n-1+j},
\end{align}

the sums converging absolutely in $H$. Recall $P_k^n$ from (2.2). From (2.16), we have

$$P_n^1X_m = \sum_{j=1}^{n} g_1^m(n,j)X_{-j} + \sum_{m_1=0}^{\infty} b_{n+1+m_1}^m X_{-n-1-m_1}.$$  

From this and (2.17), it follows that

$$P_n^2P_n^1X_m = \sum_{j=1}^{n} g_1^m(n,j)X_{-j} + \sum_{m_1=0}^{\infty} b_{n+1+m_1}^m \sum_{j=1}^{\infty} b_j^m X_{-n-1+j}$$

$$= \sum_{j=1}^{n} (g_1^m(n,j) + g_2^m(n,j))X_{-j} + \sum_{m_1=0}^{\infty} b_{n+1+m_1}^m \sum_{m_2=0}^{\infty} b_{n+1+m_2}^m X_{m_2}.$$  

Similarly,

$$P_n^3P_n^2P_n^1X_m = \sum_{j=1}^{n} (g_1^m(n,j) + g_2^m(n,j))X_{-j}$$

$$+ \sum_{m_1=0}^{\infty} b_{n+1+m_1}^m \sum_{m_2=0}^{\infty} b_{n+1+m_2}^m \sum_{j=1}^{\infty} b_j^m X_{-j}$$

$$= \sum_{j=1}^{n} (g_1^m(n,j) + g_2^m(n,j) + g_3^m(n,j))X_{-j}$$

$$+ \sum_{m_1=0}^{\infty} b_{n+1+m_1}^m \sum_{m_2=0}^{\infty} b_{n+1+m_2}^m \sum_{m_3=0}^{\infty} b_{n+1+m_3}^m X_{n-1-m_3}.$$  

Repeating this argument, we see that $\phi_{n,j}^k(X_m)$ in Lemma 2.1 with $Y = X_m$ are given by $\phi_{n,j}^k(X_m) = \sum_{l=1}^{k} g_l^m(n,j)$. The condition (2.15) implies $\sum_{0}^{\infty} (a_n)^2 < \infty$, whence (1.3) [see, e.g., Proposition 4.2 in Inoue (2000)]. Thus the theorem follows from Theorem 2.2.

\[ \square \]

2.3. Representation by absolutely convergent series. In the applications which we discuss later, the finite predictor coefficients $\phi_{n,j}$ in (1.1) need to be expressed by an absolutely convergent series made up of $a_k$ and $c_k$. In this section, we first give such an expression for $b_n^m(n,j)$. In the 1-step case $m = 0$, the result yields the desired representation for $\phi_{n,j}$.

We write $R_0$ for the class of slowly varying functions at infinity: the class of positive, measurable $\ell(\cdot)$, defined on some neighborhood $[A, \infty)$ of infinity, such that $\lim_{x \to \infty} \ell(\lambda x)/\ell(x) = 1$ for all $\lambda > 0$ [see Chapter 1 in Bingham, Goldie and Teugels (1989) for background].
Throughout this section, we assume that the stationary process \( \{X_n\} \) satisfies one of the following conditions (A1) and (A2):

(A1) \( \{X_n\} \) is purely nondeterministic, and \( \{a_n\} \) and \( \{c_n\} \) satisfy, respectively, (2.15) and

\[
\sum_{n=0}^{\infty} |c_n| < \infty.
\]

(A2) \( \{X_n\} \) is purely nondeterministic, and, for \( d \in (0, 1/2) \) and \( \ell(\cdot) \in \mathcal{R}_0 \), \( \{c_n\} \) and \( \{a_n\} \) satisfy, respectively,

\[
\begin{align*}
&c_n \sim n^{-(1-d)} \ell(n), \quad n \to \infty, \\
a_n \sim n^{-(1+d)} \frac{1}{\ell(n)} \frac{d \sin(\pi d)}{\pi}, \quad n \to \infty.
\end{align*}
\]

It should be noticed that (2.20) implies (2.15).

In this paper, we say that a stationary process \( \{X_n\} \) has long memory (respectively, short memory) if \( \sum_{k=\infty}^{\infty} |\gamma(k)| = \infty \) (respectively, \( < \infty \)). See Beran [(1994), page 6] and Section 13.2 in Brockwell and Davis (1991). By (2.12), the autocovariance function \( \gamma(\cdot) \) has the expression

\[
\gamma(n) = \sum_{k=0}^{\infty} c_{|n|+k} c_k, \quad n \in \mathbb{Z}.
\]

Hence, (2.18) implies that

\[
\sum_{n=0}^{\infty} |\gamma(n)| \leq \left( \sum_{k=0}^{\infty} |c_k| \right)^2 < \infty.
\]

Thus \( \{X_n\} \) has short memory under (A1). On the other hand, by (2.21) and Inoue [(1997), Proposition 4.3], (2.19) implies that

\[
\gamma(n) \sim n^{-(1-2d)} \ell(n)^2 B(d, 1-2d), \quad n \to \infty.
\]

Since \( 0 < 1-2d < 1 \), we see that \( \{X_n\} \) has long memory under (A2). We remark that, under suitable conditions, (2.19), (2.20) and (2.22) are equivalent [see Theorem 5.1 in Inoue (2000)].

**Example 2.6.** For \( d \in (-1/2, 1/2) \) and \( p, q \in \mathbb{N} \cup \{0\} \), a stationary process \( \{X_n\} \) is said to be a fractional ARIMA\((p, d, q)\) process if it has a spectral density \( \Delta(\cdot) \) of the form

\[
\Delta(\lambda) = \frac{1}{2\pi} \frac{|\theta(e^{i\lambda})|^2}{|\phi(e^{i\lambda})|^2} |1-e^{i\lambda}|^{-2d}, \quad -\pi \leq \lambda \leq \pi,
\]

where \( \phi(z) \) and \( \theta(z) \) are polynomials with real coefficients of degrees \( p, q \), respectively. We assume that \( \phi(z) \) and \( \theta(z) \) have no common zeros, and that neither \( \phi(z) \)
nor \( \theta(z) \) has zeros in the closed unit disk \( \{ z \in \mathbb{C} : |z| \leq 1 \} \). We also assume without loss of generality that \( \theta(0)/\phi(0) > 0 \). Then the outer function \( h(\cdot) \) is given by \( h(z) = (1 - z)^{-d} \theta(z) / \phi(z) \) [see, e.g., Section 2 in Inoue (2002)]. If \( 0 < d < 1/2 \), then \( \{ X_n \} \) satisfies (A2) for some constant function \( \ell(\cdot) \) [see Corollary 3.1 in Kokoszka and Taqqu (1995)]. If \( d = 0 \), then \( \{ X_n \} \) is also called an ARMA\((p,q)\) process [see Chapter 3 in Brockwell and Davis (1991)], and both \( \{ c_n \} \) and \( \{ a_n \} \) decay exponentially, whence (A1) is satisfied.

We put
\[
B_n := \sum_{v=0}^{\infty} |c_v a_{n+v}|, \quad n \in \mathbb{N} \cup \{0\}.
\]
For \( n, k, u, v \in \mathbb{N} \cup \{0\} \), we define \( D_k(n, u, v) \) recursively by
\[
\begin{align*}
D_0(n, u, v) &:= \delta_{u, v}, \\
D_{k+1}(n, u, v) &:= \sum_{w=0}^{\infty} B_{n+v+w} D_k(n, u, w).
\end{align*}
\]
We have, for example,
\[
D_3(n, u, v) = \sum_{v_1=0}^{\infty} \sum_{v_2=0}^{\infty} B_{n+v_1+v_2} B_{n+v_1+v_2+v_2+u}.
\]
By the Fubini–Tonelli theorem, we have
\[
D_k(n, u, v) = D_k(n, v, u).
\]

**Lemma 2.7.** We assume either (A1) or (A2). Then, for \( k, n, v \in \mathbb{N} \cup \{0\} \),
\[
\sum_{u=0}^{\infty} D_k(n, u, v) < \infty \quad \text{and} \quad \sum_{u=0}^{\infty} D_k(n, u, v)^2 < \infty,
\]
respectively. In particular, we have \( D_k(n, u, v) < \infty \) for \( k, n, u, v \in \mathbb{N} \cup \{0\} \).

**Proof.** First we assume (A1). Then
\[
\sum_{m=0}^{\infty} B_m \leq \left\{ \sum_{u=0}^{\infty} |c_u| \right\} \left\{ \sum_{u=0}^{\infty} |a_u| \right\} < \infty.
\]
This and the nonnegativity of \( B_m \) imply, for example,
\[
\sum_{u=0}^{\infty} D_3(n, u, v) = \sum_{u=0}^{\infty} \sum_{v_1=0}^{\infty} \sum_{v_2=0}^{\infty} B_{n+v_1+v_2} B_{n+v_1+v_2+v_2+u} \leq \left\{ \sum_{m=0}^{\infty} B_m \right\}^3 < \infty.
\]
The general case can be proved in the same way.

Next we assume (A2). The proof in this case is the same as that of Lemma 2.1 in Inoue (2001). By (A2) and Proposition 4.3 in Inoue (1997), we have \( B_n = O(n^{-1}) \) as \( n \to \infty \). Therefore, for \( n \in \mathbb{N} \), \( f_n \mapsto \sum_{v=0}^{\infty} B_{n+v} f_v \) defines a bounded linear operator on \( l^2 \) [see Chapter IX in Hardy, Littlewood and Pólya (1952)]. Since
$$D_{k+1}(n, u, v) = \sum_w B_{n+u+w} D_k(n, w, v),$$

we obtain the desired result by induction on $k$. \hfill \square

We put

$$\beta_n := \sum_{v=0}^{\infty} c_v a_v + n, \quad n = 0, 1, \ldots.$$  \hfill (2.23)

In view of Lemma 2.7, we may define $\delta_k(n, u, v)$ recursively by, for $k, n, u, v \in \mathbb{N}$,

$$\begin{cases} 
\delta_0(n, u, v) = \delta_{uv}, \\
\delta_{k+1}(n, u, v) = \sum_{w=0}^{\infty} \beta_{n+v+w} \delta_k(n, u, w).
\end{cases}$$  \hfill (2.24)

By Lemma 2.7 and the Fubini theorem, we have $\delta_k(n, u, v) = \delta_k(n, v, u)$.

The following theorem expresses $b^m_k(n, j)$ by an absolutely convergent series.

**Theorem 2.8.** We assume either (A1) or (A2). Then, for $n, k \in \mathbb{N}$ and $m, j \in \mathbb{N} \cup \{0\}$,

$$b^m_k(n, j) = \sum_{v=0}^{m} c_{m-v} \sum_{u=0}^{\infty} a_{j+u} \delta_{k-1}(n+1, u, v),$$  \hfill (2.25)

the sum converging absolutely.

**Proof.** By Lemma 2.7 and (2.15), we have

$$\sum_{u=0}^{\infty} |a_{j+u}| D_{k-1}(n+1, u, v) \leq \{\sup_u D_{k-1}(n+1, u, v)\} \sum_{u=0}^{\infty} |a_{j+u}| < \infty.$$  \hfill (2.26)

Thus, the right-hand side of (2.25), which we denote by $B^m_k(n, j)$, converges absolutely. To prove the proposition, it is enough show that $B^m_k(n, j)$ satisfies the same recursion as (2.14).

First we have

$$B^m_1(n, j) = \sum_{v=0}^{m} c_{m-v} \sum_{u=0}^{\infty} a_{j+u} \delta_{uv} = \sum_{v=0}^{m} c_{m-v} a_{j+v} = b^m_j,$$
as desired. Next, the Fubini–Tonelli theorem and (2.26) yield, for $k \geq 1$,

$$
\sum_{u=0}^{\infty} a_{j+u} \delta_k(n+1, u, v) = \sum_{u=0}^{\infty} \sum_{w=0}^{\infty} \left\{ \sum_{m_1=w}^{\infty} c_{m_1-u} a_{n+1+v+m_1} \right\} \delta_{k-1}(n+1, u, w)
$$

$$
= \sum_{m_1=0}^{\infty} a_{n+1+v+m_1} \sum_{w=0}^{m_1} c_{m_1-w} \sum_{u=0}^{\infty} a_{j+u} \delta_{k-1}(n+1, u, w)
$$

$$
= \sum_{m_1=0}^{\infty} a_{n+1+v+m_1} B_k^{m_1}(n, j),
$$

so that

$$
B_{k+1}^m(n, j) = \sum_{v=0}^{m} c_{m-v} \sum_{m_1=0}^{\infty} a_{n+1+v+m_1} B_k^{m_1}(n, j)
$$

$$
= \sum_{m_1=0}^{\infty} \left\{ \sum_{v=0}^{m} c_{m-v} a_{n+1+v+m_1} \right\} B_k^{m_1}(n, j) = \sum_{m_1=0}^{\infty} b_{n+1+v+m_1} B_k^{m_1}(n, j).
$$

Thus $B_k^m(n, j)$ satisfies (2.14).

For applications in later sections, we consider the case $m = 0$ separately. We put

$$
d_k(n, j) := \delta_k(n, 0, j), \quad n, k, j \in \mathbb{N} \cup \{0\}.
$$

Then, by (2.24), $d_k(n, j)$ satisfies the following recursion: for $k, n, j \in \mathbb{N} \cup \{0\}$,

$$
\begin{align*}
\begin{cases}
d_0(n, j) = \delta_{j0}, \\
d_{k+1}(n, j) = \sum_{v=0}^{\infty} \beta_{n+j+v} d_k(n, v).
\end{cases}
\end{align*}
$$

(2.27)

More explicitly, $d_k(n, j)$ are given by, for $n, j \in \mathbb{N} \cup \{0\}$,

$$
d_1(n, j) = \beta_{n+j}, \quad d_2(n, j) = \sum_{v_1=0}^{\infty} \beta_{n+j+v_1} \beta_{n+v_1},
$$

and, for $k = 3, 4, \ldots$,

$$
d_k(n, j) = \sum_{v_1=0}^{\infty} \cdots \sum_{v_{k-1}=0}^{\infty} \beta_{n+j+v_{k-1}} \beta_{n+v_{k-1}+v_{k-2}} \cdots \beta_{n+v_{2}+v_1} \beta_{n+v_1},
$$

the sums converging absolutely.

We put

$$
b_k(n, j) := b_k^0(n, j), \quad g_k(n, j) := g_k^0(n, j)
$$

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for \((k, n, j)\) for which the right-hand sides are defined. Then, for \(n \in \mathbb{N}\) and \(j = 1, 2, \ldots, n\), we have

\[
\begin{align*}
\mathcal{g}_k(n, j) &= \begin{cases} 
\mathcal{b}_k(n, j), & k = 1, 3, \ldots, \\
\mathcal{b}_k(n, n + 1 - j), & k = 2, 4, \ldots.
\end{cases}
\end{align*}
\]

By Theorems 2.5 and 2.8, we immediately obtain the following final form of the representation of the 1-step finite predictor coefficients \(\phi_{n,j}\).

**Theorem 2.9.** We assume either (A1) or (A2). Then, for \(n \in \mathbb{N}\) and \(j = 1, \ldots, n\), we have \(\phi_{n,j} = \sum_{k=1}^{\infty} \mathcal{g}_k(n, j)\) with (2.28) and

\[
\begin{cases}
\mathcal{b}_1(n, v) = c_0 a_v, & v \geq 0, \\
\mathcal{b}_k(n, v) = c_0 \sum_{u=0}^{\infty} a_{v+u} d_{k-1}(n + 1, u), & k \geq 2, v \geq 0,
\end{cases}
\]

the sum on the right-hand side converging absolutely.

3. **The rate of convergence of finite predictor coefficients**

If the stationary process \(\{X_n\}\) is PND and satisfies (2.15), then we have the Wiener prediction formula (2.16) with \(m = 0\) or (1.4) with

\[
\phi_j = c_0 a_j, \quad j \in \mathbb{N}.
\]

We call \(\phi_j\) the infinite predictor coefficients. It holds that

\[
\lim_{n \to \infty} \phi_{n,j} = \phi_j, \quad j \in \mathbb{N}
\]
[see, e.g., Theorem 7.14 in Pourahmadi (2001)]. In this section, we investigate the rate for long memory processes, at which \(\phi_{n,j}\) converges to \(\phi_j\). Notice that, by (2.14), (2.28) and (3.1), we have

\[
\phi_j = \mathcal{b}_1(n, j) = \mathcal{g}_1(n, j), \quad n \in \mathbb{N}, \ j = 1, \ldots, n.
\]

Thus \(\phi_j\) is the first term of the series \(\sum_{k=1}^{\infty} \mathcal{g}_k(n, j)\) in Theorem 2.9 expressing \(\phi_{n,j}\).

This suggests the usefulness of the expression for our purpose.

Throughout this section, we assume that the stationary process \(\{X_n\}\) satisfies (A2) in Section 2.3 (long memory).

For \(u \geq 0\), we put

\[
f_1(u) := \frac{1}{\pi(1 + u)}, \quad f_2(u) := \frac{1}{\pi^2} \int_{0}^{\infty} \frac{ds_1}{(s_1 + 1)(s_1 + 1 + u)},
\]
Proof. Let Proposition 3.2. \( \text{(i)} \) and, for \( k \in 3, 4, \ldots \),

\[
f_k(u) := \frac{1}{\pi^k} \int_0^\infty ds_{k-1} \cdots \int_0^\infty ds_1 \frac{1}{(s_{k-1} + 1) \cdots (s_1 + 1 + u)} \times \left\{ \prod_{m=1}^{k-2} \frac{1}{(s_{m+1} + s_m + 1)} \right\}
\]

[see Section 3 in Inoue (2002); see also Section 6 in Inoue (2000)].

\[
\text{Lemma 3.4 in Inoue (2001).}
\]

Thus, the assertion (i) follows from Lemma 6.5 in Inoue (2000), while (ii) from (3.3)

\[
\sum_{k=1}^{\infty} f_{2k-1}(0)x^{2k-1} = \pi^{-1} \arcsin x \text{ for } |x| < 1.
\]

Recall \( d_k(n, u) \) from Section 2.3.

\textbf{Proposition 3.2.} \( \text{(i)} \) For \( r \in (1, \infty) \), there exists \( N \in \mathbb{N} \) such that

\[
0 < d_k(n, u) \leq \frac{f_k(0)[r \sin(\pi d)]^k}{n}, \quad u \in \mathbb{N} \cup \{0\}, \quad k \in \mathbb{N}, \quad n \geq N.
\]

\( \text{(ii)} \) For \( k \in \mathbb{N} \) and \( u \in \mathbb{N} \cup \{0\} \), \( d_k(n, u) \sim n^{-1} f_k(0) \sin(\pi d) \) as \( n \to \infty \).

\textbf{Proof.} Let \( r > 1 \). Recall \( \beta_n \) from (2.23). The condition (A2) implies

\[
\beta_n \sim \frac{\sin(\pi d)}{\pi} n^{-1}, \quad n \to \infty
\]

[see Proposition 4.3 in Inoue (1997)]. Thus, for \( n \) large enough,

\[
0 < \beta_{|ns| + n + u} \leq \frac{r^{1/2} \sin(\pi d)}{\pi ([ns] + n + u)}, \quad s \geq 0, \quad u \in \mathbb{N} \cup \{0\}.
\]

Since we have, for \( n \) large enough,

\[
\frac{1}{|ns| + n + u} \leq \frac{r^{1/2}}{n(s+1)}, \quad s \geq 0, \quad u \in \mathbb{N} \cup \{0\},
\]

there exists \( N_1 \in \mathbb{N} \) such that

\[
0 < \beta_{|ns| + n + u} \leq \frac{r \sin(\pi d)}{\pi(s+1)^{n-1}}, \quad s \geq 0, \quad u \in \mathbb{N} \cup \{0\}, \quad n \geq N_1.
\]
In the same way, we can choose $N_2$ so that

$$0 < \beta_{[ns_2]+[ns_1]+n} \leq \frac{r \sin(\pi d)}{\pi(s_2 + s_1 + 1)}n^{-1}, \quad s_1, s_2 \geq 0, \quad n \geq N_2. \tag{3.7}$$

Therefore, we have, for $n \geq N := \max(N_1, N_2),

$$0 < d_3(n, u) = \int_0^\infty ds_2 \int_0^\infty ds_1 \cdot \beta_{[ns_2]+n} \cdot \beta_{[ns_2]+[ns_1]+n} \cdot \beta_{[ns_1]+n+u}$$

$$= n^2 \int_0^\infty ds_2 \int_0^\infty ds_1 \cdot \beta_{[ns_2]+n} \cdot \beta_{[ns_2]+[ns_1]+n} \cdot \beta_{[ns_1]+n+u}$$

$$\leq \frac{(r \sin(\pi d))^3}{n} \frac{1}{\pi^3} \int_0^\infty ds_2 \int_0^\infty ds_1 \frac{1}{(s_2 + 1)(s_2 + s_1 + 1)(s_1 + 1)}$$

$$= \frac{(r \sin(\pi d))^3}{n} f_3(0),$$

which implies (3.4) with $k = 3$. Notice that $N$ is independent of the choice $k = 3$.

We can prove (3.4) for general $k$ and the same $N$ in a similar fashion.

We also prove (ii) only for $k = 3$; the general case can be treated in the same way. By (3.5), we have

$$\lim_{n \to \infty} n \beta_{[ns]+n+u} = \frac{\sin(\pi d)}{\pi(s + 1)}, \quad s \geq 0, \quad u \in \mathbb{N} \cup \{0\}, \tag{3.8}$$

$$\lim_{n \to \infty} n \beta_{[ns_2]+[ns_1]+n} = \frac{\sin(\pi d)}{\pi(s_2 + s_1 + 1)}, \quad s_1, s_2 \geq 0. \tag{3.9}$$

By (3.6)–(3.9) and the dominated convergence theorem, we obtain

$$\lim_{n \to \infty} \int_0^\infty ds_2 \int_0^\infty ds_1 \cdot n \beta_{[ns_2]+n} \cdot n \beta_{[ns_2]+[ns_1]+n} \cdot n \beta_{[ns_1]+n+u}$$

$$= \frac{\sin^3(\pi d)}{\pi^3} \int_0^\infty ds_2 \int_0^\infty ds_1 \frac{1}{(s_2 + 1)(s_2 + s_1 + 1)(s_1 + 1)}$$

This implies $\lim_n nd_3(n, u) = \sin^3(\pi d)f_3(0)$ or (ii) with $k = 3$, as desired. \qed

The following theorem gives the rate for long memory processes, at which $\phi_{n,j}$ converges to $\phi_j$. It applies, in particular, to the fractional ARIMA($p, d, q$) processes with $0 < d < 1/2$.

**Theorem 3.3.** We assume (A2). Then we have, for $j \in \mathbb{N},$

$$\lim_{n \to \infty} n \{\phi_{n,j} - \phi_j\} = d^2 \sum_{u=j}^\infty \phi_u.$$

**Proof.** Let $r > 1$ be chosen so that $0 < r \sin(\pi d) < 1$. By Lemma 3.1,

$$\sum_{k=1}^\infty f_k(0)\{r \sin(\pi d)\}^k < \infty. \tag{3.10}$$
Let $N$ be such that (3.4) holds. Then, for $n \geq N$ and $j = 1, \ldots, n$,

$$n \left| \sum_{u=0}^{\infty} a_{n-j+u} \sum_{k=1}^{\infty} d_{2k-1}(n,u) \right| \leq \sum_{u=0}^{\infty} |a_{n-j+u}| \sum_{k=1}^{\infty} nd_{2k-1}(n,u)$$

so that

$$\lim_{n \to \infty} n \sum_{u=0}^{\infty} a_{n-j+u} \sum_{k=1}^{\infty} d_{2k-1}(n,u) = 0.$$

Proposition 3.2, Lemma 3.1, and the dominated convergence theorem yield

$$\lim_{n \to \infty} n \sum_{u=0}^{\infty} a_{n-j+u} \sum_{k=1}^{\infty} d_{2k-1}(n,u) = \left( \sum_{k=1}^{\infty} f_{2k}(0) \sin(\pi d) \right)^{2k-1} \sum_{u=0}^{\infty} \sum_{k=1}^{\infty} d_{2k-1}(n,u) a_u.$$

Therefore, by Theorem 2.9 and (3.2), we have

$$\lim_{n \to \infty} n \left\{ \phi_{n-1,j} - \phi_j \right\} = \lim_{n \to \infty} \left\{ \sum_{k=1}^{\infty} b_{2k+1}(n-1,j) + n \sum_{k=1}^{\infty} b_{2k}(n-1,n-j) \right\} = \lim_{n \to \infty} c_0 n \sum_{u=0}^{\infty} a_{n-1+u} \sum_{k=1}^{\infty} d_{2k}(n,u) + \lim_{n \to \infty} c_0 n \sum_{u=0}^{\infty} a_{n-j+u} \sum_{k=1}^{\infty} d_{2k-1}(n,u) = c_0 d^2 \sum_{u=j}^{\infty} a_u,$$

as desired.

4. Baxter’s inequality for long memory processes

In this section, we prove Baxter’s inequality (1.5).

**Theorem 4.1.** We assume (A2). Then there exists a positive constant $M$ such that (1.5) holds for all $n \in \mathbb{N}$. 

Proposition 3.4. We assume (A2). If $N$ is such that (3.4) holds for some $r \in (1, \infty)$, then $\sum_{k=1}^{\infty} |g_k(n,j)| < \infty$ for $n \geq N$ and $j = 1, \ldots, n$.

For processes with short memory, we have the following result.

**Proposition 3.5.** We assume (A1). If $N$ is such that $\left( \sum_{j=0}^{\infty} |c_j| \right) \left( \sum_{k=N+1}^{\infty} |a_k| \right) < 1$, then $\sum_{k=1}^{\infty} |g_k(n,j)| < \infty$ for $n \geq N$ and $j = 1, \ldots, n$.

We omit the proof.
Proof. Let \( r > 1 \) be chosen so that \( 0 < r \sin(\pi d) < 1 \). Then we have (3.10). By Proposition 3.2 and (2.20), we may take a positive integer \( N \) such that both (3.4) and \( a_n > 0 \) hold for \( n \geq N \). Pick \( \delta \in (0, d) \). By (2.20) and Bingham, Goldie and Teugels [(1989), Theorem 1.5.6 (iii)] (Potter-type bounds), we may assume that

\[
a_m/a_n \leq 2 \max\{(n/m)^{1+d-\delta}, (m/n)^{1+d+\delta}\}, \quad m, n \geq N.
\]

(4.1)

By Theorem 2.9 and (3.2), we have, for \( n \geq N + 3 \),

\[
\sum_{j=1}^{n-1} |\phi_{n-1,j} - \phi_j| \leq c_0 \sum_{j=1}^{n-1} \sum_{u=0}^{\infty} |a_{u+j}| \sum_{k=1}^{\infty} d_{2k}(n, u) + c_0 \sum_{j=1}^{n-1} \sum_{u=0}^{\infty} |a_{u+n-j}| \sum_{k=1}^{\infty} d_{2k-1}(n, u)
\]

\[
= c_0 \sum_{k=1}^{\infty} \sum_{u=0}^{\infty} d_k(n, u) \sum_{j=1}^{n-1} |a_{u+j}| = c_0 \{G_1(n) + G_2(n)\},
\]

where

\[
G_1(n) := \sum_{k=1}^{\infty} \sum_{u=0}^{\infty} d_k(n, u) \sum_{j=1}^{n+1} |a_{u+j}|,
\]

\[
G_2(n) := \sum_{k=1}^{\infty} \sum_{u=0}^{\infty} d_k(n, u) \sum_{j=N+2}^{n-1} a_{u+j}.
\]

For \( n \geq N + 3 \), we have

\[
G_1(n) \leq n^{-1} \left[ \sum_{k=1}^{\infty} f_k(0) (r \sin(\pi d))^k \right] \sum_{j=1}^{n+1} \sum_{u=0}^{\infty} |a_{u+j}|,
\]

and

\[
G_2(n) \leq \sum_{k=1}^{\infty} \int_0^{\infty} du \cdot d_k(n, [u]) \int_{\frac{a_{[u]+[s]+2}}{a_{n}}}^{1} \frac{a_{[u]+[s]+2}}{a_{n}} ds
\]

\[
= an \sum_{k=1}^{\infty} \int_0^{\infty} du \cdot d_k(n, [nu]) \int_{\frac{a_{[nu]+[ns]+2}}{a_{n}}}^{1} \frac{a_{[nu]+[ns]+2}}{a_{n}} ds.
\]

By (4.1), we have, for \( u > 0 \), \( n \geq N + 3 \), and \( N/n \leq s \leq 1 \),

\[
\frac{a_{[nu]+[ns]+2}}{a_{n}} \leq 2 \max\left\{ \left(\frac{n}{[nu]+[ns]+2}\right)^{1+d+\delta}, \left(\frac{n}{[nu]+[ns]+2}\right)^{1-\delta+d}\right\}
\]

\[
\leq 2 \max\{(u+s)^{-(1+d+\delta)}, (u+s)^{-(1+d-\delta)}\}.
\]

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Hence, by (3.4),

\[ G_2(n) \leq 2 \int_0^1 ds \int_0^\infty \left\{ (u+s)^{-(1+d+\delta)} + (u+s)^{-(1+d-\delta)} \right\} du \]

\[ \times na_n \left[ \sum_{k=1}^\infty f_k(0) \{r \sin(\pi d)\}^k \right] \]

\[ \leq 2 \left\{ \frac{1}{(\delta + d)(1-d-\delta)} + \frac{1}{(d-\delta)(1-d+\delta)} \right\} \]

\[ \times na_n \left[ \sum_{k=1}^\infty f_k(0) \{r \sin(\pi d)\}^k \right]. \]

Combining these estimates, we obtain

\[ \limsup_{n \to \infty} \left\{ n^{d\ell(n)} \sum_{j=1}^{n-1} |\phi_{n-1,j} - \phi_j| \right\} < \infty. \]

Since \( \sum_{k=n}^\infty \phi_k = c_0 \sum_{k=n}^\infty a_k \sim c_0 \sin(\pi d)/\{\pi n^{d\ell(n)}\} \) as \( n \to \infty \), the theorem follows.

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