A CLASS OF ORTHOGONAL FUNCTIONS GIVEN BY A
THREE TERM RECURRENCE FORMULA

C. F. BRACCIALI, J. H. McCABE, T. E. PÉREZ, AND A. SRI RANGA

Abstract. We present a class of functions satisfying a certain orthogonality
property for which there also exists a three term recurrence formula. This class
of functions, which can be considered as an extension to the class of symmetric
orthogonal polynomials on \([-1,1]\), has a complete connection to the orthogonal
polynomials on the unit circle. Interpolatory properties, quadrature rules and
other properties based on the zeros of these functions are also considered.

1. Introduction

Let \(P_m\) be the linear space of real polynomials of degree at most \(m\) and let \(\Omega_m\)
be the linear space of “real” functions on \([-1,1]\) defined as follows: \(\Omega_0 \equiv P_0\) and
\(\Omega_m\), for \(m \geq 1\), is such that if \(F \in \Omega_m\), then \(F(x) = B^{(0)}(x) + \sqrt{1-x^2} B^{(1)}(x)\),
where \(B^{(0)} \in P_m\) and \(B^{(1)} \in P_{m-1}\) satisfy

\[
B^{(0)}(-x) = (-1)^m B^{(0)}(x) \quad \text{and} \quad B^{(1)}(-x) = (-1)^{m-1} B^{(1)}(x).
\]

This means, if \(F \in \Omega_{2n}\), then \(B^{(0)}\) is an even polynomial of degree at most \(2n\) and
\(B^{(1)}\) is an odd polynomial of degree at most \(2n - 1\). Likewise, if \(F \in \Omega_{2n+1}\), then
\(B^{(0)}\) is an odd polynomial of degree at most \(2n + 1\) and \(B^{(1)}\) is an even polynomial
of degree at most \(2n\).

Note that the dimension of \(\Omega_m\) is \(m + 1\). As an example of a basis for \(\Omega_{2n}\) we have

\[
\{1, x\sqrt{1-x^2}, x^2, \ldots, x^{2n-1}\sqrt{1-x^2}, x^{2n}\}
\]

and as an example of a basis for \(\Omega_{2n+1}\) we can state

\[
\{\sqrt{1-x^2}, x, x^2\sqrt{1-x^2}, \ldots, x^{2n}\sqrt{1-x^2}, x^{2n+1}\}.
\]

It is important to observe that, if \(F \in \Omega_m\), then for all \(k \geq 1\),

\[F \in \Omega_{m+2k}\quad \text{but} \quad F \notin \Omega_{m+2k-1}.
\]
For $\mathcal{F}(x) = B^{(0)}(x) + \sqrt{1 - x^2} B^{(1)}(x) \in \Omega_m$, by setting

$$B^{(0)}(x) = \sum_{j=0}^{\lfloor m/2 \rfloor} b_{2j}^{(0)} x^{m-2j} \quad \text{and} \quad B^{(1)}(x) = \sum_{j=0}^{\lfloor (m-1)/2 \rfloor} b_{2j}^{(1)} x^{m-1-2j},$$

we say that the function $\mathcal{F}$ is of exact degree $m$ if $(b_0^{(0)})^2 + (b_0^{(1)})^2 > 0$. The coefficients $b_0^{(0)}$ and $b_0^{(1)}$ will be referred to as the first and second leading coefficients of $\mathcal{F}$, respectively. The positive number $(b_0^{(0)})^2 + (b_0^{(1)})^2$ may be called the lead factor of $\mathcal{F}$.

Our interest in the study of such functions is broad. Apart from the interesting properties such as the three term recurrence formula, orthogonality and quadrature formulas that can be associated with these functions as shown in this manuscript, the solution of the differential equation

$$(1 - x^2)\mathcal{F}''(x) - [(2\lambda + 1)x - 2\eta\sqrt{1 - x^2}] \mathcal{F}'(x) + m [m + 2\lambda + \frac{2\eta x}{\sqrt{1 - x^2}}] \mathcal{F}(x) = 0,$$

with integer $m$, is also among these types of functions (see [7]). Note that when $\eta = 0$, the solution of the above differential equation is the ultraspherical polynomial of degree $m$ (see, for example, [4, 19]).

Our studies of these functions were also motivated by the interesting example (Example 2) given in Section 7 of this manuscript. The function $\hat{W}_m$ given in this example is exactly a solution of the above differential equation.

Another benefit for studying these types of functions is that with $x = \cos(\theta)$ we can obtain trigonometric polynomials with interesting properties. For example, as a consequence of results obtained in [7], the use of the three term recurrence formula (1.1) below with the choice $\gamma_m = 1$, $m \geq 0$, $\{\beta_m\}_{m=1}^\infty$ a real sequence and $\{\alpha_m\}_{m=2}^\infty$ a positive chain sequence, permits one to generate a sequence of trigonometric polynomials having complete sets of simple zeros in $(0, \pi)$. Precisely, $W_m(\cos(\theta))$ would be a trigonometric polynomial of degree $m$ with exactly $m$ simple zeros in $(0, \pi)$.

We will also describe in Section 6 of this manuscript the connection that these functions have with orthogonal polynomials on the unit circle (OPUC). In the contexts of OPUC, some properties of functions of a somewhat similar appearance, but without the even odd parity conditions that we have imposed here, have been studied in [1].

The specific aim of the present manuscript is to consider some properties, in particular, the orthogonal properties of the sequence of functions $\{W_m\}$, where $W_m \in \Omega_m$, given by

$$W_0(x) = \gamma_0, \quad W_1(x) = (\gamma_1 x - \beta_1 \sqrt{1 - x^2}) \gamma_0,$$

$$W_{m+1}(x) = [\gamma_{m+1} x - \beta_{m+1} \sqrt{1 - x^2}] W_m(x) - \alpha_{m+1} W_{m-1}(x), \quad m \geq 1.$$

Here, $\{\alpha_m\}_{m=2}^\infty$, $\{\beta_m\}_{m=1}^\infty$ and $\{\gamma_m\}_{m=0}^\infty$ are sequences of real numbers.

2. Functions in $\Omega_m$ and Self-Inversive Polynomials

It is known that a polynomial $Q_m$ of degree at most $m$ is self-inversive of degree $m$ if $z^m Q_m(\overline{z}) = c_m Q_m(z)$, where $|c_m| = 1$. As one of the earliest references to self-inversive polynomials we cite Bonsall and Marden [2]. The most interesting self-inversive polynomials are those polynomials with all their zeros on the unit
circle. Characterizing self-inversive polynomials with zeros on the unit circle has been of considerable interest (see, for example, [13,15,18]).

In this manuscript we adopt the definition that 

$$Q_m(z) = z^m Q_m(1/z) = Q_m(z).$$

Note that we have assumed \( c_m = 1 \) from the original definition of self-inversive polynomials. We remark that what is considered in the present manuscript as self-inversive polynomials are, as in [18], also known as conjugate reciprocal polynomials.

Functions belonging to \( \Omega_m \) are connected to self-inversive polynomials of degree \( m \). That is, given \( F_m \in \Omega_m \) then associated with it there exists a unique \( Q_m \) which is a self-inversive polynomial of degree \( m \). Precisely, \( e^{-im\theta/2} Q_m(e^{i\theta}) = F_m(x) \), where \( x = \cos(\theta/2) \).

The following lemma, which will be of considerable use in this manuscript, gives a more precise statement regarding this connection.

**Lemma 2.1.** Let \( x = \cos(\theta/2) \). Then the polynomial \( Q_m \) is self-inversive of degree \( m \) if and only if

$$e^{-im\theta/2} Q_m(e^{i\theta}) = F_m(x) = B_m^{(0)}(x) + \sqrt{1 - x^2} B_m^{(1)}(x) \in \Omega_m.$$ 

Thus, \( |Q_m(e^{i\theta})|^2 = [B_m^{(0)}(x) + \sqrt{1 - x^2} B_m^{(1)}(x)]^2 \) and \( Q_m(1) = B_m^{(0)}(1) \).

Moreover, \( Q_m \) is a self-inversive polynomial with real coefficients if and only if \( B_m^{(1)} \) is identically zero.

**Proof.** This lemma has also been stated and proved in [8]. However, for completeness and for a better understanding of the use of this lemma, we give here a sketch of its proof.

Given any polynomial \( Q_m \) of degree at most \( m \), not necessarily self-inversive, by setting \( Q_m(z) = \sum_{j=0}^m (c_j^{(m)} + i d_j^{(m)}) z^j \) we can write

$$z^{-m+1/2} Q_{2m-1}(z) = \sum_{j=0}^{m-1} (c_{m-1-j}^{(2m-1)} + c_{m+j}^{(2m-1)}) \frac{z^{j+1/2} + z^{-j-1/2}}{2}$$

$$- \sum_{j=0}^{m-1} i(d_{m-1-j}^{(2m-1)} - d_{m+j}^{(2m-1)}) \frac{z^{j+1/2} - z^{-j-1/2}}{2}$$

$$+ \sum_{j=0}^{m-1} i(d_{m-1-j}^{(2m-1)} + d_{m+j}^{(2m-1)}) \frac{z^{j+1/2} + z^{-j-1/2}}{2}$$

$$- \sum_{j=0}^{m-1} (c_{m-1-j}^{(2m-1)} - c_{m+j}^{(2m-1)}) \frac{z^{j+1/2} - z^{-j-1/2}}{2}$$
and 
\[ z^{-m}Q_{2m}(z) = c^{(2m)}_m + i d^{(2m)}_m \]
\[ + \sum_{j=1}^m \left[ (c^{(2m)}_{m-j} + c^{(2m)}_{m+j}) \frac{z^j + z^{-j}}{2} - i(d^{(2m)}_{m-j} - d^{(2m)}_{m+j}) \frac{z^j - z^{-j}}{2} \right] \]
\[ + \sum_{j=1}^m \left[ i(d^{(2m)}_{m-j} + d^{(2m)}_{m+j}) \frac{z^j + z^{-j}}{2} - (c^{(2m)}_{m-j} - c^{(2m)}_{m+j}) \frac{z^j - z^{-j}}{2} \right] . \]

Then for \( z = e^{i\theta} \), with \( x = (z^{1/2} + z^{-1/2})/2 = \cos(\theta/2) \), we obtain
\[ e^{-im\theta/2}Q_{m}(e^{i\theta}) = F_m(x) + i \tilde{F}_m(x) \quad \text{and} \quad |Q_{m}(e^{i\theta})|^2 = [F_m(x)]^2 + [\tilde{F}_m(x)]^2, \]
where the functions \( F_m \) and \( \tilde{F}_m \), defined for \( x \in [-1,1] \), satisfy
\[ F_{2m-1}(x) = \sum_{j=0}^{m-1} (c^{(2m-1)}_{m-j} + c^{(2m-1)}_{m+j}) T_{2j+1}(x) + (d^{(2m-1)}_{m-j} - d^{(2m-1)}_{m+j}) \sqrt{1-x^2} U_{2j}(x), \]
\[ \tilde{F}_{2m-1}(x) = \sum_{j=0}^{m-1} (d^{(2m-1)}_{m-j} + d^{(2m-1)}_{m+j}) T_{2j+1}(x) - (c^{(2m-1)}_{m-j} - c^{(2m-1)}_{m+j}) \sqrt{1-x^2} U_{2j-1}(x), \]
\[ F_{2m}(x) = c^{(2m)}_m + \sum_{j=1}^m (c^{(2m)}_{m-j} + c^{(2m)}_{m+j}) T_{2j}(x) + (d^{(2m)}_{m-j} - d^{(2m)}_{m+j}) \sqrt{1-x^2} U_{2j-1}(x), \]
\[ \tilde{F}_{2m}(x) = d^{(2m)}_m + \sum_{j=1}^m (d^{(2m)}_{m-j} + d^{(2m)}_{m+j}) T_{2j}(x) - (c^{(2m)}_{m-j} - c^{(2m)}_{m+j}) \sqrt{1-x^2} U_{2j-1}(x). \]

Here,
\[ T_j(x) = \cos(j\theta/2) \quad \text{and} \quad U_j(x) = \frac{\sin((j+1)\theta/2)}{\sin(\theta/2)} \]
\[ = \frac{1}{2}(z^{j/2} + z^{-j/2}) \quad \text{and} \quad \frac{(z^{(j+1)/2} - z^{-(j+1)/2})}{(z^{1/2} - z^{-1/2})}, \]
are respectively the Chebyshev polynomials of the first and second kind.

These relations enable one to establish a connection between any polynomial \( Q_m(z) \) and the functions \( F_m(x) \) and \( \tilde{F}_m(x) \) both in \( \Omega_m \).

However, if \( Q_m(z) = \sum_{j=0}^m (c^{(m)}_j + i d^{(m)}_j) z^j \) is self-inversive, that is, \( Q^*_m(z) = Q_m(z) \), then \( c^{(m)}_j = c^{(m)}_{m-j} \) and \( d^{(m)}_j = -d^{(m)}_{m-j} \) and hence \( \tilde{F}_m(x) \) is identically zero. This proves the first part of the lemma. To obtain the latter part of the lemma, we use \( c^{(m)}_j = c^{(m)}_{m-j} \) and \( d^{(m)}_j = -d^{(m)}_{m-j} = 0 \).

Within the contexts of the latter part of Lemma 2.1 the transformation \( x = (z^{1/2} + z^{-1/2})/2 = \cos(\theta/2) \), sometimes known as the DG-transformation, has been used by many, including \([3,6,21]\), to explore the connection between real OPUC and symmetric orthogonal polynomials in \([-1,1]\).

Since a polynomial of degree at most \( m \) cannot have more than \( m \) zeros on the unit circle, an immediate consequence of Lemma 2.1 is the following.

**Theorem 2.2.** Let \( F \in \Omega_m \). Then the number of zeros of \( F \) in \((-1,1) \) cannot exceed \( m \). Moreover, if \( 1 \) is a zero of \( F \), then \(-1 \) is also a zero of \( F \), and in this case the number of zeros of \( F \) in \([-1,1] \) cannot exceed \( m + 1 \).
Another interesting result regarding functions in \( \Omega_m \) is their interpolation property, which is virtually the interpolation property of self-inversive polynomials on the unit circle \(|z| = 1\). Results regarding interpolation by polynomials, including the idea behind the proof of the theorem below, are well known and can be found in any numerical analysis texts. For a recent reference of such a text we cite [14].

**Theorem 2.3.** Given the \( m + 1 \) pairs of real numbers \((x_j, f_j)\), \( j = 1, 2, \ldots, m + 1\), where \(-1 < x_1 < x_2 < \ldots < x_{m+1} < 1\), then there exists a unique \( \mathcal{F} \in \Omega_m \) such that

\[
\mathcal{F}(x_j) = f_j, \quad j = 1, 2, \ldots, m + 1.
\]

Moreover, this interpolation function can be given by

\[
(2.1) \quad \mathcal{F}(x) = \sum_{k=1}^{m+1} \mathcal{L}_k(x) f_k,
\]

where

\[
\mathcal{L}_k(x) = z^{-m/2} z_k^{m/2} \prod_{l \neq k}^{m+1} \frac{z - z_l}{z_k - z_l}, \quad k = 1, 2, \ldots, m + 1,
\]

with \( z = e^{i\theta}, \theta = 2 \arccos(x) \), \( z_k = e^{i\theta_k} \) and \( \theta_k = 2 \arccos(x_k) \).

**Proof.** Uniqueness follows from Theorem 2.2. That is, if \( \mathcal{F} \) and \( \hat{\mathcal{F}} \) are two different functions in \( \Omega_m \) such that

\[
\mathcal{F}(x_j) = f_j \quad \text{and} \quad \hat{\mathcal{F}}(x_j) = f_j, \quad j = 1, 2, \ldots, m + 1,
\]

then \( \mathcal{G} \), where \( \mathcal{G}(x) = \mathcal{F}(x) - \hat{\mathcal{F}}(x) \in \Omega_m \) and \( \mathcal{G}_{m}(x) \neq 0 \), has \( m + 1 \) zeros in \((-1, 1)\) contradicting Theorem 2.2.

To show the existence we construct the required function as follows. It is easily seen that the scaled Lagrange polynomials

\[
z_k^{m/2} \prod_{l \neq k}^{m+1} \frac{z - z_l}{z_k - z_l}, \quad k = 1, 2, \ldots, m + 1,
\]

defined on the set \( \{z_1, z_2, \ldots, z_m\} \) are self-inversive. Consequently, \( \mathcal{L}_k \) are in \( \Omega_m \) and they satisfy

\[
\mathcal{L}_k(x_j) = \delta_{jk}, \quad j = 1, 2, \ldots, m + 1.
\]

Hence, the formula (2.1) immediately leads to the required interpolation function.

\( \square \)

3. Some basic properties

**Theorem 3.1.** Let the sequence functions \( \{\mathcal{F}_m\} \), where \( \mathcal{F}_0(x) = b_{0,0}^{(0)} \).

\[
\mathcal{F}_m(x) = \sum_{j=0}^{\lfloor m/2 \rfloor} b_{m,2j}^{(0)} x^{m-2j} + \sqrt{1 - x^2} \sum_{j=0}^{\lfloor (m-1)/2 \rfloor} b_{m,2j}^{(1)} x^{m-1-2j}, \quad m \geq 1,
\]

be such that \( b_{m+1,0}^{(0)} b_{m,0}^{(0)} + b_{m+1,0}^{(1)} b_{m,0}^{(1)} \neq 0 \), \( m \geq 0 \). Here, \( b_{0,0}^{(1)} = 0 \). Then the following hold:

1. A basis for \( \Omega_{2m} \) is

\[
\{\mathcal{F}_{2m}(x), \sqrt{1 - x^2} \mathcal{F}_{2m-1}(x), \mathcal{F}_{2m-2}(x), \ldots, \mathcal{F}_2(x), \sqrt{1 - x^2} \mathcal{F}_1(x), \mathcal{F}_0(x)\};
\]
2. A basis for \( \Omega_{2m+1} \) is
\[
\{ F_{2m+1}(x), \sqrt{1 - x^2} F_{2m}(x), F_{2m-1}(x), \ldots, \sqrt{1 - x^2} F_2(x), F_1(x), \sqrt{1 - x^2} F_0(x) \}.
\]

Proof. Since \( b_{m+1,0}^{(0)} b_{m,0}^{(0)} + b_{m+1,0}^{(1)} b_{m,0}^{(1)} \neq 0 \) for \( m \geq 0 \) implies \( (b_{m,0}^{(0)})^2 + (b_{m,0}^{(1)})^2 > 0 \)
for \( m \geq 0 \), the function \( F_m \) is of exact degree \( m \) for \( m \geq 0 \).

Now to prove the theorem, by observing that the dimension of \( \Omega_m \) is \( m + 1 \), all we have to do is to verify that the above sets are linearly independent. We prove this for the even indices and the proof for the odd indices is similar.

Clearly, \( F_0(x) = b_{0,0}^{(0)} \neq 0 \) is a basis for \( \Omega_0 \). Now we verify that
\[
\{ F_2(x), \sqrt{1 - x^2} F_1(x), F_0(x) \}
\]
is a basis for \( \Omega_2 \).

Let \( c_0, c_1, c_2 \) be such that \( c_0 F_2(x) + c_1 \sqrt{1 - x^2} F_1(x) + c_2 F_0(x) = 0 \). Since the dimension of \( \Omega_2 \) is 3, we need to verify that this is possible only if \( c_0 = c_1 = c_2 = 0 \). By considering the coefficients of \( x^2 \) and \( x \sqrt{1 - x^2} \), we have
\[
c_0 b_{2,0}^{(0)} - c_1 b_{1,0}^{(1)} = 0,
\]
\[
c_0 b_{2,0}^{(1)} + c_1 b_{1,0}^{(0)} = 0.
\]
The determinant of this system is \( b_{2,0}^{(0)} b_{1,0}^{(1)} + b_{2,0}^{(1)} b_{1,0}^{(0)} \), which is different from zero. We must therefore have \( c_0 = c_1 = 0 \). This reduces our verification to finding \( c_2 \) such that \( c_2 F_0(x) = 0 \). Clearly, \( c_2 = 0 \), which follows from \( F_0(x) = b_{0,0}^{(0)} \neq 0 \).

Now assuming
\[
(3.1) \quad \{ F_{2m}(x), \sqrt{1 - x^2} F_{2m-1}(x), F_{2m-2}(x), \ldots, F_2(x), \sqrt{1 - x^2} F_1(x), F_0(x) \}
\]
is a basis for \( \Omega_{2m} \), we show that
\[
\{ F_{2m+2}(x), \sqrt{1 - x^2} F_{2m+1}(x), F_{2m}(x), \ldots, F_2(x), \sqrt{1 - x^2} F_1(x), F_0(x) \}
\]
is a basis for \( \Omega_{2m+2} \). Let \( c_0, c_1, c_2, \ldots, c_{2m+1}, c_{2m+2} \) be such that
\[
c_0 F_{2m+2}(x) + c_1 \sqrt{1 - x^2} F_{2m+1}(x) + \ldots + c_{2m+1} \sqrt{1 - x^2} F_1(x) + c_{2m+2} F_0(x) = 0.
\]
By considering the coefficients of \( x^{2m+2} \) and \( x^{2m+1} \sqrt{1 - x^2} \), we have
\[
c_0 b_{2m+2,0}^{(0)} - c_1 b_{2m+1,0}^{(1)} = 0,
\]
\[
c_0 b_{2m+2,0}^{(1)} + c_1 b_{2m+1,0}^{(0)} = 0.
\]
The determinant of this system is \( b_{2m+2,0}^{(0)} b_{1,0}^{(1)} + b_{2m+2,0}^{(1)} b_{1,0}^{(0)} \). Since this determinant is different from zero, we must have \( c_0 = c_1 = 0 \). This reduces our verification to finding \( c_2, c_3, \ldots, c_{2m+2} \), such that
\[
c_2 F_{2m}(x) + c_3 \sqrt{1 - x^2} F_{2m-1}(x) + \ldots + c_{2m+1} \sqrt{1 - x^2} F_1(x) + c_{2m+2} F_0(x) = 0.
\]
Clearly, \( c_2 = c_3 = \ldots = c_{2m+1} = c_{2m+2} = 0 \), which follow from the assumption in (3.1). Thus, the results of the theorem for even indices follow by induction. \( \square \)

Now with the assumptions \( \gamma_0 \neq 0, \gamma_1 \neq 0 \) and \( \gamma_m^2 + \beta_m^2 > 0, m \geq 2 \), we consider the functions \( W_m \) given by the recurrence formula (1.1). It is easily seen that \( W_m \) takes the form
\[
W_m(x) = A_m^{(0)}(x) + \sqrt{1 - x^2} A_m^{(1)}(x),
\]
where
where $A_m^{(0)}$ and $A_m^{(1)}$ are, respectively, polynomials of degree at most $m$ and $m - 1$, such that
\[ A_m^{(0)}(-x) = (-1)^m A_m^{(0)}(x) \quad \text{and} \quad A_m^{(1)}(-x) = (-1)^{m-1} A_m^{(1)}(x). \]

Hence, $W_m \in \Omega_m, m \geq 0$. Setting
\[ (3.3) \quad A_m^{(0)}(x) = \sum_{j=0}^{\lfloor m/2 \rfloor} a_m^{(0), j} x^{m-2j} \quad \text{and} \quad A_m^{(1)}(x) = \sum_{j=0}^{\lfloor (m-1)/2 \rfloor} a_m^{(1), j} x^{m-1-2j}, \]
we have the following.

**Theorem 3.2.** With $\gamma_0 \neq 0$, $\gamma_1 \neq 0$ and $\gamma_m^2 + \beta_m^2 > 0$, $m \geq 2$, let $\{W_m\}$ be the sequence of functions obtained from the three term recurrence formula (1.1). Then with respect to the leading coefficients $a_m^{(0), 0}$ and $a_m^{(1), 0}$ and the lead factor
\[ \lambda_m = (a_m^{(0), 0})^2 + (a_m^{(1), 0})^2 \]
of $W_m$ given by (3.2) and (3.3), the following hold:
\[ \begin{bmatrix} a_m^{(0), 0} \\ a_m^{(1), 0} \end{bmatrix} = \begin{bmatrix} \gamma_m & \beta_m \\ -\beta_m & \gamma_m \end{bmatrix} \begin{bmatrix} a_m^{(0), 0} \\ a_m^{(1), 0} \end{bmatrix}, \quad m \geq 1, \]
with $a_0^{(0), 0} = \gamma_0$ and $a_0^{(1), 0} = 0$. Consequently,
\[ \lambda_0 = \gamma_0^2, \quad \lambda_m = (\gamma_m^2 + \beta_m^2) \lambda_{m-1}, \quad m \geq 1, \]
\[ \lambda_{m, 1} = a_{m+1, 0}^{(0), 0} + a_{m+1, 0}^{(1), 0} = \gamma_{m+1} \lambda_m, \quad m \geq 0, \]
\[ a_{m+1, 0}^{(0), 0} a_{m, 0}^{(1), 0} - a_{m+1, 0}^{(0), 0} a_{m, 0}^{(0), 0} = \beta_{m+1} \lambda_m, \quad m \geq 0, \]
\[ a_{m+1, 0}^{(0), 0} a_{m-1, 0}^{(0), 0} + a_{m+1, 0}^{(1), 0} a_{m-1, 0}^{(1), 0} = (\gamma_m \gamma_{m+1} - \beta_m \beta_{m+1}) \lambda_{m-1}, \quad m \geq 1 \]
and
\[ a_{m+1, 0}^{(0), 0} a_{m-1, 0}^{(1), 0} - a_{m+1, 0}^{(0), 0} a_{m-1, 0}^{(0), 0} = (\gamma_{m+1} \beta_m + \gamma_m \beta_{m+1}) \lambda_{m-1}, \quad m \geq 1. \]

**Proof.** From (1.1), (3.2) and (3.3), by equating the coefficients of $x^{m+1}$ and $x^m \sqrt{1-x^2}$,
\[ (3.4) \quad a_{m+1, 0}^{(0), 0} = \gamma_{m+1} a_{m, 0}^{(0), 0} + \beta_{m+1} a_{m, 0}^{(1), 0}, \]
\[ a_{m+1, 0}^{(1), 0} = -\beta_{m+1} a_{m, 0}^{(0), 0} + \gamma_{m+1} a_{m, 0}^{(1), 0}. \]

From these the matrix formula in the theorem follows. The equalities and recurrence can be obtained as follows.

From the matrix formula,
\[ (a_m^{(0), 0})^2 + (a_m^{(1), 0})^2 = \begin{bmatrix} a_m^{(0), 0} & a_m^{(1), 0} \end{bmatrix} \begin{bmatrix} a_m^{(0), 0} \\ a_m^{(1), 0} \end{bmatrix} \]
\[ = \begin{bmatrix} a_m^{(0), 0} & a_m^{(1), 0} \\ a_m^{(0), 0} & a_m^{(1), 0} \end{bmatrix} \begin{bmatrix} \gamma_m & -\beta_m \\ \beta_m & \gamma_m \end{bmatrix} \begin{bmatrix} a_m^{(0), 0} \\ a_m^{(1), 0} \end{bmatrix}. \]

Thus,
\[ (a_m^{(0), 0})^2 + (a_m^{(1), 0})^2 = \begin{bmatrix} a_m^{(0), 0} & a_m^{(1), 0} \end{bmatrix} \begin{bmatrix} \gamma_m^2 + \beta_m^2 & 0 \\ 0 & \gamma_m^2 + \beta_m^2 \end{bmatrix} \begin{bmatrix} a_m^{(0), 0} \\ a_m^{(1), 0} \end{bmatrix} \]
\[ = (\gamma_m^2 + \beta_m^2) (a_m^{(0), 0})^2 + (a_m^{(1), 0})^2 = (\gamma_m^2 + \beta_m^2) \lambda_{m-1}, \]
which gives the recurrence formula for $\lambda_m$. Similarly,

$$a^{(0)}_{m+1,0} a^{(0)}_{m,0} + a^{(1)}_{m+1,0} a^{(1)}_{m,0} = \begin{bmatrix} a^{(0)}_{m,0} & a^{(1)}_{m,0} \\ a^{(0)}_{m+1,0} & a^{(1)}_{m+1,0} \end{bmatrix}$$

$$= \begin{bmatrix} a^{(0)}_{m,0} & a^{(1)}_{m,0} \\ a^{(0)}_{m+1,0} & a^{(1)}_{m+1,0} \end{bmatrix} \begin{bmatrix} \gamma_{m+1} & \beta_{m+1} \\ -\beta_{m+1} & \gamma_{m+1} \end{bmatrix} \begin{bmatrix} a^{(0)}_{m,0} \\ a^{(1)}_{m,0} \end{bmatrix}$$

$$= \gamma_{m+1} [(a^{(0)}_{m,0})^2 + (a^{(1)}_{m,0})^2] = \gamma_{m+1} \lambda_m.$$

From (3.4),

$$a^{(0)}_{m+1,0} a^{(1)}_{m,0} - a^{(1)}_{m+1,0} a^{(0)}_{m,0}$$

$$= [\gamma_{m+1} a^{(0)}_{m,0} + \beta_{m+1} a^{(1)}_{m,0}] a^{(0)}_{m,0} - [-\beta_{m+1} a^{(0)}_{m,0} + \gamma_{m+1} a^{(1)}_{m,0}] a^{(0)}_{m,0}$$

$$= \beta_{m+1} [(a^{(0)}_{m,0})^2 + (a^{(1)}_{m,0})^2] = \beta_{m+1} \lambda_m.$$

Again from (3.4),

$$a^{(0)}_{m+1,0} a^{(0)}_{m-1,0} + a^{(1)}_{m+1,0} a^{(1)}_{m-1,0}$$

$$= [\gamma_{m+1} a^{(0)}_{m,0} + \beta_{m+1} a^{(1)}_{m,0}] a^{(0)}_{m-1,0} + [-\beta_{m+1} a^{(0)}_{m,0} + \gamma_{m+1} a^{(1)}_{m,0}] a^{(0)}_{m-1,0}$$

$$= \gamma_{m+1} [a^{(0)}_{m,0} a^{(0)}_{m-1,0} + a^{(1)}_{m,0} a^{(1)}_{m-1,0}] - \beta_{m+1} [a^{(0)}_{m,0} a^{(0)}_{m-1,0} - a^{(1)}_{m,0} a^{(1)}_{m-1,0}]$$

$$= (\gamma_{m+1} - \beta_m \beta_{m+1}) \lambda_m - a^{(0)}_{m+1,0} a^{(0)}_{m,0} - a^{(1)}_{m+1,0} a^{(1)}_{m,0}$$

Similarly, the value associated with $a^{(0)}_{m+1,0} a^{(0)}_{m-1,0} - a^{(1)}_{m+1,0} a^{(1)}_{m-1,0}$ is also obtained.

Clearly, with the assumptions $\gamma_0 \neq 0$, $\gamma_1 \neq 0$ and $\beta_m^2 + \gamma_m^2 > 0$, $m \geq 2$, it holds that

$$\lambda_m = (a^{(0)}_{m,0})^2 + (a^{(1)}_{m,0})^2 > 0, \quad m \geq 0,$$

which means the leading coefficients of $A^{(0)}_m$ and $A^{(1)}_m$ cannot be zero simultaneously and $W_m \in \Omega_m$ is of exact degree $m$.

With a more restrictive condition than $\gamma_0 \neq 0$, $\gamma_1 \neq 0$ and $\beta_m^2 + \gamma_m^2 > 0$, $m \geq 2$, we state the following theorem.

**Theorem 3.3.** Let $\gamma_m \neq 0$, $m \geq 0$ and let $\{W_m\}$ be the sequence of functions given by the recurrence formula (1.1). Then for any $m \geq 0$,

1. A basis for $\Omega_{2m}$ is

$$\{W_{2m}(x), \sqrt{1-x^2} W_{2m-1}(x), W_{2m-2}(x), \ldots, W_2(x), \sqrt{1-x^2} W_1(x), W_0(x)\}.$$

2. A basis for $\Omega_{2m+1}$ is

$$\{W_{2m+1}(x), \sqrt{1-x^2} W_{2m}(x), \ldots, \sqrt{1-x^2} W_2(x), W_1(x), \sqrt{1-x^2} W_0(x)\}.$$

**Proof.** From Theorem 3.2 we observe that, with $\gamma_m \neq 0$, $m \geq 0$, the leading coefficients of $W_m$, $m \geq 0$ are such that $\lambda_{m,1} = a^{(0)}_{m+1,0} a^{(0)}_{m,0} + a^{(1)}_{m+1,0} a^{(1)}_{m,0} \neq 0$, $m \geq 0$. Hence, the present theorem follows from Theorem 3.1. \qed
Finally, by denoting the self-inversive polynomial associated with $W_m$ by $K_m$, we have the following.

**Theorem 3.4.** Let $K_m(x) = \sum_{j=0}^{m} k_j^{(m)} x^j$ be such that

$$e^{-im\theta/2} K_m(e^{i\theta}) = W_m(x),$$

where $x = \cos(\theta/2)$. Then

$$k_0^{(m)} = \overline{k_0^{(m)}} = 2^{-m} [a_{m,0}^{(0)} + i a_{m,0}^{(1)}] \quad \text{and} \quad |k_0^{(m)}|^2 = |k_0^{(m)}|^2 = 2^{-2m} \lambda_m.$$  

4. **Orthogonal properties associated with $W_m$**

Let $\psi$ be a positive measure on $[-1,1]$. We consider the sequence of functions $\{W_m\}$, where $W_m \in \Omega_m$ is of exact degree $m$, is such that

$$\int_{-1}^{1} W_{2n}(x) W_{2m}(x) \sqrt{1-x^2} \, d\psi(x) = \rho_{2m} \delta_{n,m},$$

$$\int_{-1}^{1} W_{2n+1}(x) W_{2m+1}(x) \sqrt{1-x^2} \, d\psi(x) = \rho_{2m+1} \delta_{n,m},$$

$$\int_{-1}^{1} W_{2n+1}(x) W_{2m}(x) \, d\psi(x) = 0,$$

for $n, m = 0, 1, 2, \ldots$.

We use the notation $W_0(x) = a_{0,0}^{(0)}$,

$$W_m(x) = \sum_{j=0}^{\lfloor m/2 \rfloor} a_{m,2j}^{(0)} x^{m-2j} + \sqrt{1-x^2} \sum_{j=0}^{\lfloor (m-1)/2 \rfloor} a_{m,2j}^{(1)} x^{m-1-2j}, \quad m \geq 1,$$

$$\lambda_m = (a_{m,0}^{(0)})^2 + (a_{m,0}^{(1)})^2,$$

and

$$\lambda_{m,1} = a_{m+1,0}^{(0)} a_{m,0}^{(0)} + a_{m+1,0}^{(1)} a_{m,0}^{(1)}, \quad m \geq 0,$$

with $a_{0,0}^{(1)} = 0$.

Observe that, in the case $a_{m,2j}^{(1)} = 0$, $j = 0, 1, \ldots, \lfloor (m-1)/2 \rfloor$, $m \geq 1$, then $\{W_m\}$ are symmetric polynomials and (4.1) reduces to the orthogonality of symmetric polynomials with respect to $\sqrt{1-x^2} \, d\psi(x)$ in $[-1,1]$. For references to some of the classical texts on orthogonal polynomials on the real line we cite [4][12][19].

**Theorem 4.1.** The sequence of functions $\{W_m\}$ that satisfies the orthogonality property (4.1), where $W_m \in \Omega_m$ and is of exact degree $m$, always exists. Moreover, the orthogonal sequence $\{W_m\}$ can always be given by the three term recurrence formula

$$W_0(x) = \gamma_0, \quad W_1(x) = [\gamma_1 x - \beta_1 \sqrt{1-x^2}] \gamma_0,$$

$$W_{m+1}(x) = [\gamma_{m+1} x - \beta_{m+1} \sqrt{1-x^2}] W_m(x) - \alpha_{m+1} W_{m-1}(x), \quad m \geq 1,$$
where \( \gamma_m \neq 0, m \geq 0 \), \( \beta_1 = \gamma_1 \rho_0^{-1} \int_{-1}^{1} x W_0^2(x) d\psi(x) \),
\[
(4.3) \quad \beta_{m+1} = \frac{1}{\rho_m} \int_{-1}^{1} x W_m^2(x) d\psi(x), \quad \text{and}
\]
\[
(4.4) \quad \alpha_{m+1} = \frac{1}{\rho_{m-1}} \int_{-1}^{1} [\gamma_{m+1} x - \beta_{m+1} \sqrt{1-x^2}] W_{m-1}(x) W_m(x) \sqrt{1-x^2} d\psi(x),
\]
for \( m \geq 1 \). Here, \( \rho_m = \int_{-1}^{1} W_m^2(x) \sqrt{1-x^2} d\psi(x), m \geq 0 \).

Proof. It follows from Theorem 3.2 that, with \( \gamma_m \neq 0, m \geq 0 \), the function \( W_m \) obtained from the three term recurrence formula (4.2) is such that \( W_m \in \Omega_m \) and is of exact degree \( m \). Hence, we first show that with \( \alpha_m \) and \( \beta_m \) successively chosen as in (4.3) the sequence of functions \( \{W_m\} \) generated by the above three term recurrence formula satisfies the orthogonality (4.1).

Since \( \beta_1 = \gamma_1 \rho_0^{-1} \int_{-1}^{1} x W_0^2(x) d\psi(x) \), with \( W_1(x) = [\gamma_1 x - \beta_1 \sqrt{1-x^2}] \gamma_0 \) it follows that \( \int_{-1}^{1} W_0(x) W_1(x) d\psi(x) = 0 \).

Since \( \beta_2 \) and \( \alpha_2 \) are as in (4.3), with
\[
W_2(x) = [\gamma_2 x - \beta_2 \sqrt{1-x^2}] W_1(x) - \alpha_2 W_0(x),
\]
we have
\[
\int_{-1}^{1} W_1(x) W_2(x) d\psi(x) = 0 \quad \text{and} \quad \int_{-1}^{1} W_0(x) W_2(x) \sqrt{1-x^2} d\psi(x) = 0.
\]

Now suppose that for \( N \geq 2 \) the sequence of functions \( \{W_m\}_{m=0}^{N} \) obtained from the three term recurrence formula (4.2) satisfies (4.1).

Since \( x W_{N-2k}(x) \in \Omega_{N+1-2k} \), by Theorem 3.3 there exists \( c_0, c_1, \ldots, c_{N+1-2k} \) such that
\[
x W_{N-2k}(x) = c_0 W_{N+1-2k}(x) + c_1 \sqrt{1-x^2} W_{N-2k}(x) + c_2 W_{N-1-2k}(x) + \ldots.
\]
Hence, we have
\[
\int_{-1}^{1} x W_{N-2k}(x) W_N(x) d\psi(x) = 0, \quad k = 1, 2, \ldots, [N/2].
\]
Likewise, since \( x \sqrt{1-x^2} W_{N-1-2k}(x) \in \Omega_{N+1-2k} \), we have
\[
(4.4) \quad \int_{-1}^{1} x \sqrt{1-x^2} W_{N-1-2k}(x) W_N(x) d\psi(x) = 0, \quad k = 1, 2, \ldots, [(N-1)/2]
\]
and, since \( (1-x^2) W_{N-1-2k}(x) \in \Omega_{N+1-2k} \), we also have
\[
(4.5) \quad \int_{-1}^{1} (1-x^2) W_{N-1-2k}(x) W_N(x) d\psi(x) = 0, \quad k = 1, 2, \ldots, [(N-1)/2].
\]
Note that in (4.4) and (4.5) the value of \( N \) is assumed to be \( \geq 3 \).

Hence, from
\[
W_{N+1}(x) = [\gamma_{N+1} x - \beta_{N+1} \sqrt{1-x^2}] W_N(x) - \alpha_{N+1} W_{N-1}(x),
\]
it follows that
\[
\int_{-1}^{1} W_{N-2k}(x) W_{N+1}(x) \, d\psi(x) = 0, \quad k = 1, 2, \ldots, \lfloor N/2 \rfloor,
\]
\[
\int_{-1}^{1} W_{N-2k}(x) W_{N+1}(x) \sqrt{1-x^2} \, d\psi(x) = 0, \quad k = 1, 2, \ldots, \lfloor (N-1)/2 \rfloor.
\]
Moreover, since \(\alpha_{N+1} \) and \(\beta_{N+1} \) are as in (4.3), we also have
\[
\int_{-1}^{1} W_{N}(x) W_{N+1}(x) \, d\psi(x) = 0,
\]
\[
\int_{-1}^{1} W_{N-1}(x) W_{N+1}(x) \sqrt{1-x^2} \, d\psi(x) = 0.
\]
Thus, by induction we conclude that the sequence of functions given by the three term recurrence formula satisfies (4.1).

On the other hand, to show that any sequence of functions \(\{W_m\} \), where \(W_m \in \Omega_m \) is of exact degree \(m \), for which (4.1) holds, must also satisfy the three term recurrence formula (4.2), we proceed as follows.

Clearly we can write \(W_0(x) = \gamma_0 \neq 0 \) and \(W_1(x) = a_{1,0}^{(0)} x + a_{1,0}^{(1)} \sqrt{1-x^2} = [\gamma_1 x - \beta_1 \sqrt{1-x^2}] \gamma_0 \). Then for \(\int_{-1}^{1} W_0(x) W_1(x) \, d\psi(x) = 0 \) to hold such that \(W_1(x) \) is of exact degree 1, one must have \(\gamma_1 \neq 0 \) and \(\beta_1 = \gamma_1 \rho_0^{-1} \int_{-1}^{1} x W_0^2(x) \, d\psi(x) \).

With the next element \(W_2 \) of the given orthogonality sequence, let \(\gamma_2 \) and \(\beta_2 \) be such that \(W_2(x) = [\gamma_2 x - \beta_2 \sqrt{1-x^2}] W_1(x) \in \Omega_0 \). With respect to the leading coefficients of \(W_2 \) and \(W_1 \), the elements \(\gamma_2 \) and \(\beta_2 \) must satisfy
\[
\begin{bmatrix}
a_{2,0}^{(0)} \\
a_{2,0}^{(1)}
\end{bmatrix} = \begin{bmatrix}
a_{1,0}^{(0)} & a_{1,0}^{(1)} \\
a_{1,0}^{(1)} & -a_{1,0}^{(0)}
\end{bmatrix} \begin{bmatrix}
\gamma_2 \\
\beta_2
\end{bmatrix}.
\]

The determinant of this system is \(-[(a_{1,0}^{(0)})^2 + (a_{1,0}^{(1)})^2] \). Since \(W_1 \) is of exact degree 1 this determinant is different from zero. Hence, the values of \(\gamma_2 \) and \(\beta_2 \) are uniquely found. Writing
\[
W_2(x) = [\gamma_2 x - \beta_2 \sqrt{1-x^2}] W_1(x) - \alpha_2 W_0(x),
\]
we find, with the orthogonality and with the additional observation that \(W_2 \) is of exact degree 2, that \(\gamma_2 \neq 0 \),
\[
\beta_2 = \frac{\gamma_2}{\rho_1} \int_{-1}^{1} x W_2^2(x) \, d\psi(x) \quad \text{and}
\]
\[
\alpha_2 = \frac{1}{\rho_0} \int_{-1}^{1} [\gamma_2 x - \beta_2 \sqrt{1-x^2}] W_0(x) W_1(x) \sqrt{1-x^2} \, d\psi(x).
\]

Now for \(N \geq 2 \) assume that the orthogonal functions \(W_m, \ m = 0, 1, \ldots, N \) satisfy the three term recurrence formula (4.2), with \(\gamma_m \neq 0, \ m = 0, 1, \ldots, N \). Let \(\gamma_{N+1} \) and \(\beta_{N+1} \) be such that \(W_{N+1}(x) = [\gamma_{N+1} x - \beta_{N+1} \sqrt{1-x^2}] W_N(x) \in \Omega_{N-1} \). With respect to the leading coefficients of \(W_{N+1} \) and \(W_N \), the elements \(\gamma_{N+1} \) and \(\beta_{N+1} \) must satisfy
\[
\begin{bmatrix}
a_{N+1,0}^{(0)} \\
a_{N+1,0}^{(1)}
\end{bmatrix} = \begin{bmatrix}
a_{N,0}^{(0)} & a_{N,0}^{(1)} \\
a_{N,0}^{(1)} & -a_{N,0}^{(0)}
\end{bmatrix} \begin{bmatrix}
\gamma_{N+1} \\
\beta_{N+1}
\end{bmatrix}.
\]
The determinant of this system is $-[(a_{N,0}^{(0)})^2 + (a_{N,0}^{(1)})^2]$, which is different from zero because $W_N$ is of exact degree $N$. Hence, the values for $\gamma_{N+1}$ and $\beta_{N+1}$ are uniquely found.

Now using Theorem 3.3 there exist $c_0, c_1, \ldots, c_{N-1}$ such that

$$W_{N+1}(x) = [\gamma_{N+1}x - \beta_{N+1}\sqrt{1 - x^2}]W_N(x)$$

$$+ c_0W_{N-1}(x) + c_1\sqrt{1 - x^2}W_{N-2}(x) + c_2W_{N-3}(x) + \ldots.$$ 

Applications of the orthogonality properties (4.1) of the sequence $\{W_m\}_{m=0}^{N+1}$, together with the observation that $W_{N+1}$ is of exact degree $N+1$, lead to $c_1 = c_2 = \ldots = c_{N-1} = 0$, $\gamma_{N+1} \neq 0$,

$$\beta_{N+1} = \gamma_{N+1} \frac{1}{\rho_N} \int_{-1}^{1} x W^2_N(x) d\psi(x)$$

and

$$\alpha_{N+1} = -c_0 = \frac{1}{\rho_{N-1}} \int_{-1}^{1} [\gamma_{N+1}x - \beta_{N+1}\sqrt{1 - x^2}] W_{N-1}(x) W_N(x) \sqrt{1 - x^2} d\psi(x).$$

This concludes the proof of the theorem. □

Following as in Theorem 3.2 we have $\gamma_{m+1} = \lambda_{m,1}/\lambda_m$. Thus, the orthogonal functions $W_m$, $m \geq 1$, are such that

$$\lambda_{m,1} = a_{m+1,0}^{(0)} + a_{m+1,0}^{(1)} \neq 0, \quad m \geq 0.$$ 

**Corollary 4.1.1.** The sequence of functions $\{W_m\}$, where $W_m \in \Omega_m$ and is of exact degree $m$, satisfies the orthogonality property (4.1) if and only if, for $m \geq 1$,

$$\int_{-1}^{1} F(x) W_m(x) d\psi(x) = 0 \quad \text{whenever} \quad F \in \Omega_{m-1}.$$ 

**Proof.** First we assume that (4.6) holds. Observe that, if $F \in \Omega_{m+1-2k}$ for $k = 1, 2, \ldots, \lfloor (m + 1)/2 \rfloor$, then $F \in \Omega_{m-1}$. Hence, $W_{m+1-2k} \in \Omega_{m+1-2k}$ and $W_{m-2k} \sqrt{1 - x^2} \in \Omega_{m+1-2k}$ leads immediately to (4.1).

On the other hand, if (4.1) holds, then from Theorem 4.1 and from Theorem 3.3 we can write

$$F_{m+1-2k}(x) = c_0 W_{m+1-2k}(x) + c_1 \sqrt{1 - x^2} W_{m-2k}(x) + c_2 W_{m-1-2k}(x) + \ldots,$$

for $k = 1, 2, \ldots, \lfloor (m + 1)/2 \rfloor$. Hence, (4.6) is immediate. □

It is quite straightforward that another way to present the above corollary is the following.

**Corollary 4.1.2.** The sequence of functions $\{W_m\}$, where $W_m \in \Omega_m$ and is of exact degree $m$, satisfies the orthogonality property (4.1) if and only if, for $m \geq 1$,

$$\int_{-1}^{1} B^{(0)}(x) W_m(x) d\psi(x) = 0 \quad \text{and} \quad \int_{-1}^{1} B^{(1)}(x) W_m(x) \sqrt{1 - x^2} d\psi(x) = 0,$$

where $B^{(0)} \in \mathbb{P}_{m-1}$ and $B^{(1)} \in \mathbb{P}_{m-2}$ satisfy

$$B^{(0)}(-x) = (-1)^{m-1} B^{(0)}(x) \quad \text{and} \quad B^{(1)}(-x) = (-1)^{m-2} B^{(1)}(x).$$

The following corollary provides one other way to express the orthogonality (4.1) of the sequence $\{W_n\}$. 
Corollary 4.1.3. The sequence of functions \( \{W_m\} \), where \( W_m \in \Omega_m \) and is of exact degree \( m \), satisfies the orthogonality property \((4.1)\) if and only if, for \( m \geq 1 \),

\[
\int_{-1}^{1} (x + i \sqrt{1 - x^2})^{m+1+2s} W_m(x) \, d\psi(x) = 0, \quad s = 0, 1, \ldots, m - 1.
\]

**Proof.** We just give the proof for \( m = 2n \) and the proof for \( m = 2n + 1 \) is similar. Since \((x + i \sqrt{1 - x^2})(x - i \sqrt{1 - x^2}) = 1\) the orthogonality \((4.7)\) for \( m = 2n \) can be written as

\[
\int_{-1}^{1} (x \pm i \sqrt{1 - x^2})^{2l+1} W_{2n}(x) \, d\psi(x) = 0, \quad l = 0, 1, \ldots, n - 1.
\]

Observe that

\[
(x \pm i \sqrt{1 - x^2})^{2l+1} = \sum_{k=0}^{l} \binom{2l+1}{2k+1} x^{2k+1}(x^2 - 1)^{l-k} \pm i \sqrt{1 - x^2} \sum_{k=0}^{l} \binom{2l+1}{2k} x^{2k}(x^2 - 1)^{l-k}.
\]

Since the polynomials represented by the above sums are, respectively, odd and even polynomials of exact degrees \(2l + 1\) and \(2l\), the required result follows from Corollary 4.1.2. \(\square\)

The following theorem, in addition to showing some further orthogonality properties of the functions \( \{W_m\} \) given by Theorem 4.1, also gives another expression for the coefficients \( \alpha_n \) given in Theorem 4.1.

**Theorem 4.2.**

\[
\int_{-1}^{1} x \sqrt{1 - x^2} W_1(x) W_2(x) \, d\psi(x) = \frac{\gamma_2 \gamma_3 - \beta_2 \beta_3}{(\gamma_2^2 + \beta_2^2) \gamma_3} \rho_2,
\]

\[
\int_{-1}^{1} (1 - x^2) W_1(x) W_2(x) \, d\psi(x) = -\frac{\gamma_3 \beta_2 + \gamma_2 \beta_3}{(\gamma_2^2 + \beta_2^2) \gamma_3} \rho_2,
\]

and for \( m \geq 2 \),

\[
\int_{-1}^{1} x \sqrt{1 - x^2} W_{m-1-2k}(x) W_m(x) \, d\psi(x) = \begin{cases} \frac{\gamma_m \gamma_{m+1} - \beta_m \beta_{m+1}}{(\gamma_m^2 + \beta_m^2) \gamma_{m+1}} \rho_m, & k = 0, \\ 0, & 1 \leq k \leq \lfloor (m - 1)/2 \rfloor, \end{cases}
\]

\[
\int_{-1}^{1} (1 - x^2) W_{m-1-2k}(x) W_m(x) \, d\psi(x) = \begin{cases} -\frac{\gamma_{m+1} \beta_m + \gamma_m \beta_{m+1}}{(\gamma_{m+1}^2 + \beta_m^2) \gamma_m} \rho_m, & k = 0, \\ 0, & 1 \leq k \leq \lfloor (m - 1)/2 \rfloor. \end{cases}
\]

Consequently,

\[
\alpha_{m+1} = \frac{\gamma_{m+1}^2 + \beta_{m+1}^2}{(\gamma_m^2 + \beta_m^2) \gamma_{m+1}} \frac{\gamma_m}{\rho_m} \frac{\rho_m}{\rho_{m-1}}, \quad m \geq 1.
\]
Proof. Since \( x^k \sqrt{1 - x^2} W_{m-1-2k}(x) \) and \( (1 - x^2) W_{m-1-2k}(x) \) are in \( \Omega_{m+1-2k} \), the results corresponding to \( 1 \leq k \leq \lfloor (m-1)/2 \rfloor \) follow from Corollary 4.1.1.

We now prove the result associated with \( \int_{-1}^{1} x^k \sqrt{1 - x^2} W_{m-1}(x) W_{m}(x) d\psi(x) \).

Since \( x^k \sqrt{1 - x^2} W_{m-1}(x) \in \Omega_{m+1} \), there exist \( c_0, c_1, \ldots, c_{m+1} \) such that

\[
x^k \sqrt{1 - x^2} W_{m-1}(x) = c_0 W_{m+1}(x) + c_1 \sqrt{1 - x^2} W_{m}(x) + c_2 W_{m-1}(x) + \ldots
\]

and that \( \int_{-1}^{1} x^k \sqrt{1 - x^2} W_{m-1}(x) W_{m}(x) d\psi(x) = c_1 \rho_m \).

Moreover, comparing the leading coefficients on both sides

\[
-a_{m-1,0} = c_0 a_{m+1,0} - c_1 a_{m,0},
\]

\[
a_{m-1,0} = c_0 a_{m+1,0} + c_1 a_{m,0}.
\]

This gives \( c_1 = \left[ a_{m+1,0} a_{m-1,0} + a_{m+1,0} a_{m-1,0} \right] / \left[ a_{m+1,0} a_{m,0} + a_{m+1,0} a_{m,0} \right] \). Thus, from Theorem 3.2 we have

\[
c_1 = \frac{\gamma_m \gamma_{m+1} - \beta_m \beta_{m+1}}{(\gamma_m^2 + \beta_m^2) \gamma_{m+1}}
\]

and the required result for \( \int_{-1}^{1} x^k \sqrt{1 - x^2} W_{m-1}(x) W_{m}(x) d\psi(x) \).

The result associated with \( \int_{-1}^{1} (1 - x^2) W_{m-1}(x) W_{m}(x) d\psi(x) \) is obtained similarly, and the latter result of the theorem then follows from (4.3).

Now we can state the following theorem with respect to the zeros of \( W_m \).

**Theorem 4.3.** Let \( \{W_m\} \) be the sequence of functions given as in Theorem 4.1. Then for \( m \geq 1 \), the function \( W_m \) has exactly \( m \) distinct zeros in \((-1, 1)\).

**Proof.** From (4.1) since at least one of the integrals

\[
\int_{-1}^{1} W_0(x) W_m(x) d\psi(x) \quad \text{and} \quad \int_{-1}^{1} W_0(x) W_m(x) \sqrt{1 - x^2} d\psi(x)
\]

is zero, we can say that \( W_m \) changes sign at least once in \((-1, 1)\). According to Theorem 2.2, the number of sign changes of \( W_m \) also cannot exceed \( m \).

Suppose that \( W_m(x) \) changes sign \( k \) times \( (1 \leq k \leq m) \) times in \((-1, 1)\), namely at the points \( y_1, y_2, \ldots, y_k \).

Let \( \theta_j = 2 \arccos(y_j) \), \( j = 1, 2, \ldots, k \) and consider the self-inversive polynomial (of degree \( k \)) defined by

\[
q_k(z) = e^{-i(k\pi + \theta_1 + \theta_2 + \ldots + \theta_k)/2}(z - e^{i\theta_1})(z - e^{i\theta_2}) \cdots (z - e^{i\theta_k}).
\]

Now, with \( x = \cos(\theta/2) = (z^{1/2} + z^{-1/2})/2 \), if we consider the function \( F_k \) given by

\[
F_k(x) = e^{-ik\theta/2} q_k(e^{i\theta}),
\]

then by Lemma 2.1, \( F_k \in \Omega_k \) and further \( F_k \) has exactly the \( k \) zeros \( y_1, y_2, \ldots, y_k \), which are the points of sign changes in \( W_m \). Hence, the function \( F_k(x) W_m(x) \) does not change sign in \((-1, 1)\) which then leads to the conclusion

\[
\int_{-1}^{1} F_k(x) W_m(x) d\psi(x) \neq 0 \quad \text{and} \quad \int_{-1}^{1} F_k(x) W_m(x) \sqrt{1 - x^2} d\psi(x) \neq 0.
\]

On the other hand, if \( k < m \), then from Corollary 4.1.1 at least one of the integrals

\[
\int_{-1}^{1} F_k(x) W_m(x) d\psi(x) \quad \text{and} \quad \int_{-1}^{1} F_k(x) W_m(x) \sqrt{1 - x^2} d\psi(x)
\]
must be equal to zero, contradicting the earlier conclusion. Hence, the only possibility is \( k = m \) and that \( W_m \) has \( m \) sign changes in \((-1, 1)\). That is, \( W_m \) has exactly \( m \) zeros in \((-1, 1)\).

Now we look at the sequence of functions \( \{\hat{W}_m\} \), obtained from the sequence of orthogonal functions \( \{W_m\} \) by the scaling

\[
\hat{W}_0(x) = \frac{1}{\gamma_0} W_0(x), \quad \hat{W}_m(x) = \frac{1}{\gamma_0 \cdots \gamma_m} W_m(x), \quad m \geq 0.
\]

By considering the properties of \( \{\hat{W}_m\} \) we can state the following.

**Theorem 4.4.** Let the sequence of functions \( \{\hat{W}_m\} \) be given by

\[
\hat{W}_0(x) = 1, \quad \hat{W}_1(x) = x - \hat{\beta}_1 \sqrt{1 - x^2},
\]

\[
\hat{W}_{m+1}(x) = [x - \hat{\beta}_{m+1} \sqrt{1 - x^2}] \hat{W}_m(x) - \hat{\alpha}_{m+1} \hat{W}_{m-1}(x), \quad m \geq 1,
\]

where \( \hat{\beta}_1 = \frac{1}{\rho_m} \int_{-1}^{1} x \hat{W}_0^2(x) \, d\psi(x) \) and for \( m \geq 1, \)

\[
\hat{\beta}_{m+1} = \frac{1}{\rho_m} \int_{-1}^{1} x \hat{W}_m^2(x) \, d\psi(x) \quad \text{and}
\]

\[
\hat{\alpha}_{m+1} = \frac{1}{\rho_{m-1}} \int_{-1}^{1} [x - \hat{\beta}_{m+1} \sqrt{1 - x^2}] \hat{W}_{m-1}(x) \hat{W}_m(x) \sqrt{1 - x^2} \, d\psi(x)
\]

\[
= \frac{1 + \hat{\beta}_{m+1}^2}{1 + \hat{\beta}_m^2} \hat{\rho}_m.
\]

Here, \( \hat{\rho}_m = \int_{-1}^{1} \hat{W}_m^2(x) \sqrt{1 - x^2} \, d\psi(x), \quad m \geq 0. \) Then \( \{\hat{W}_m\} \), where \( \hat{W}_m \in \Omega_m \) and is of exact degree \( m \), satisfies the orthogonality (4.1).

Observe that \( \hat{\alpha}_{m+1} > 0, \quad m \geq 1. \) In fact (see Theorem 6.2), more can be said about these coefficients if the measure \( \psi \) is such that \( \int_{-1}^{1} (1 - x^2)^{-1/2} \, d\psi(x) \) exists.

5. **Quadrature rules associated with \( W_m \)**

In order to be able to obtain the quadrature rules based on the zeros of \( W_m \) we first present the following theorem.

**Theorem 5.1.** Let \( \{W_m\} \) be the sequence of orthogonal functions as defined before.

Given any function \( E \in \Omega_{2m-1}, \ m \geq 1, \) then associated with it there exists a unique function \( F \in \Omega_{2m-1} \) and a unique function \( G \in \Omega_{2m-1} \) such that

\[
E(x) = F(x) W_{2m}(x) + G(x).
\]

Likewise, given any \( E \in \Omega_{4m}, \ m \geq 1, \) then associated with it there exists a unique function \( F \in \Omega_{2m-1} \) and a unique function \( G \in \Omega_{2m} \) such that

\[
E(x) = F(x) W_{2m+1}(x) + G(x).
\]

**Proof.** We give a proof of the latter formula. If the formula holds then the uniqueness of \( F \) and \( G \) can be easily verified with the use of Theorem 2.3. Now to prove the existence, let \( P, \ Q, \ R \) and \( K_{2m+1} \) be the respective self-inversive polynomials associated with the functions \( E, \ F, \ G \) and \( W_{2m+1} \). Then one needs to prove that given the self-inversive-polynomial \( P \) of degree at most \( 4m \) there exists a self-inversive
polynomial $Q$ of degree at most $2m - 1$ and a self-inversive polynomial $R$ of degree at most $2m$ such that

\begin{equation}
(5.1) \quad P(z) = Q(z) K_{2m+1}(z) + z^m R(z).
\end{equation}

With the self-inversive property, we can write

\[
P(z) = \sum_{j=0}^{4m} p_j z^j = \sum_{j=0}^{2m-1} p_j z^j + p_{2m} z^{2m} + \sum_{j=2m+1}^{4m} \bar{p}_{4m-j} z^j,
\]

\[
Q(z) = \sum_{j=0}^{2m-1} q_j z^j = \sum_{j=0}^{m-1} q_j z^j + \sum_{j=m}^{2m-1} \bar{q}_{2m-j} z^j,
\]

\[
R(z) = \sum_{j=0}^{2m} r_j z^j = \sum_{j=0}^{m-1} r_j z^j + r_m z^m + \sum_{j=m+1}^{2m} \bar{r}_{2m-j} z^j,
\]

and

\[
K_{2m+1}(z) = \sum_{j=0}^{2m+1} k_j(2m+1) z^j = \sum_{j=0}^{m} k_j(2m+1) z^j + \sum_{j=m+1}^{2m+1} \bar{k}_{2m+1-j} z^j.
\]

Note that $p_{2m}$ and $r_m$ are both real.

Comparing the coefficients of the potentials $1, z, z^2, \ldots, z^{2m}$ on both sides of (5.1) we have

\[
q_0 = p_0 / k_0^{(2m+1)}
\]

\[
q_j = [p_j - \sum_{l=0}^{j-1} q_l k_j^{(2m+1)}] / k_0^{(2m+1)}, \quad j = 1, 2, \ldots, m - 1,
\]

\[
r_j = p_{m+j} - \sum_{l=0}^{m+j} q_l k_{m+j-l}^{(2m+1)}, \quad j = 0, 1, \ldots, m - 1,
\]

and

\[
r_m = p_{2m} - \sum_{l=0}^{2m-1} q_l k_{2m-l}^{(2m+1)} = p_{2m} - \sum_{l=0}^{m-1} [q_l k_{2m-l}^{(2m+1)} + q_l k_{2m-l}^{(2m+1)}].
\]

From Theorem 3.4 since $k_0^{(2m+1)} \neq 0$ the above formulas are well defined. Thus, with the further observation that equalities in the higher potentials lead to the same results, the existence of $Q$ and $R$ in (5.1) is verified.

The proof of the first formula of the theorem is similar. \hfill \square

We now look at the interpolatory type quadrature rule at the zeros of $\mathcal{W}_m$. For the notion of polynomial interpolatory quadrature rules we cite [10].

First we denote the zeros of $\mathcal{W}_m$ by $x_k^{(m)}$, $k = 1, 2, \ldots, m$ and let $z_k^{(m)} = e^{i2\arccos(x_k^{(m)})}$, $k = 1, 2, \ldots, m$. Hence, if $G \in \Omega_{m-1}$, then by Theorem 2.3 we can write

\[
G(x) = \sum_{k=1}^{m} L_{m,k}(x) G(x_k^{(m)}),
\]
where \( L_{m,k} \in \Omega_{m-1} \) are functions associated with \( W_m \), given by

\[
L_{m,k}(x) = \frac{1}{2} \left( z_k^{(m)} \right)^{m-1/2} \prod_{l=1}^{m} \frac{z_m - z_l^{(m)}}{z_k^{(m)} - z_l^{(m)}}, \quad k = 1, 2, \ldots, m,
\]

with \( x = \cos(\theta/2) \) and \( z = e^{i\theta} \). Consequently, if

\[
\hat{\lambda}_k^{(m)} = \int_{-1}^{1} L_{m,k}(x) \, d\psi(x) \quad \text{and} \quad \overline{\lambda}_k^{(m)} = \int_{-1}^{1} L_{m,k}(x) \sqrt{1-x^2} \, d\psi(x),
\]

for \( k = 1, 2, \ldots, m \) then, for any \( G \in \Omega_{m-1} \), we have the following interpolatory quadrature rules

\[
\begin{align*}
\int_{-1}^{1} G(x) \, d\psi(x) &= \sum_{k=1}^{m} \hat{\lambda}_k^{(m)} G(x_k^{(m)}), \quad (5.2) \\
\int_{-1}^{1} G(x) \sqrt{1-x^2} \, d\psi(x) &= \sum_{k=1}^{m} \overline{\lambda}_k^{(m)} G(x_k^{(m)}).
\end{align*}
\]

Clearly, these quadrature rules hold for any distinct set of points \( x_k^{(m)}, k = 1, 2, \ldots, m \). However, since \( x_k^{(m)} \) are the zeros of the functions \( W_m \) we can say more.

**Theorem 5.2.** Let \( x_k^{(m)}, k = 1, 2, \ldots, m \) be the zeros of \( W_m \) and let

\[
\lambda_k^{(m)} = \int_{-1}^{1} [L_{m,k}(x)]^2 \sqrt{1-x^2} \, d\psi(x), \quad k = 1, 2, \ldots, m.
\]

If \( E \in \Omega_{4m-1}, m \geq 1 \), then

\[
\int_{-1}^{1} E(x) \, d\psi(x) = \sum_{k=1}^{2m} \frac{1}{\sqrt{1 - (x_k^{(2m)})^2}} \lambda_k^{(2m)} E(x_k^{(2m)})
\]

and if \( E \in \Omega_{4m}, m \geq 0 \), then

\[
\int_{-1}^{1} E(x) \sqrt{1-x^2} \, d\psi(x) = \sum_{k=1}^{2m+1} \lambda_k^{(2m+1)} E(x_k^{(2m+1)}).
\]

**Proof.** To obtain the first quadrature, with \( E \in \Omega_{4m-1} \) we have from Theorem 5.1 that there exist \( F \in \Omega_{2m-1} \) and \( G \in \Omega_{2m-1} \) such that \( E(x) = F(x) W_{2m}(x) + G(x) \). Hence, from the orthogonality given by Corollary 4.1.1 it follows that

\[
\int_{-1}^{1} E(x) \, d\psi(x) = \int_{-1}^{1} G(x) \, d\psi(x).
\]

Therefore, from \( E(x_k^{(2m)}) = G(x_k^{(2m)}) \), \( k = 1, 2, \ldots, 2m \) and from (5.2), we have

\[
\int_{-1}^{1} E(x) \, d\psi(x) = \sum_{k=1}^{2m} \hat{\lambda}_k^{(2m)} E(x_k^{(2m)}),
\]

which holds for \( E \in \Omega_{4m-1} \). With the choice \( E(x) = \sqrt{1-x^2} [L_{2m,j}(x)]^2 \in \Omega_{4m-1} \) we then obtain that

\[
\hat{\lambda}_j^{(2m)} = \frac{1}{\sqrt{1 - (x_j^{(2m)})^2}} \lambda_j^{(2m)}, \quad j = 1, 2, \ldots, 2m.
\]
Now to obtain the latter quadrature rule, with $E \in \Omega_{4m}$ it follows from Theorem 5.1 that there exist $F \in \Omega_{2m-1}$ and $G \in \Omega_{2m}$ such that $E(x) = F(x) W_{2m+1}(x) + G(x)$. This leads to the interpolatory quadrature rule

$$
\int_{-1}^{1} E(x) \sqrt{1-x^2} \, d\psi(x) = \sum_{k=1}^{2m+1} \lambda_k^{(2m+1)} E(x_k^{(2m+1)}),
$$

which holds for $E \in \Omega_{4m}$. With the choice $E(x) = [L_{2m+1,j}(x)]^2 \in \Omega_{4m}$ we then obtain that

$$
\bar{\lambda}_j^{(2m+1)} = \lambda_j^{(2m+1)}, \quad j = 1, 2, \ldots, 2m + 1.
$$

This completes the proof of the theorem.

Since $\lambda_k^{(m)}$ in Theorem 5.2 are all positive, we can now state the following theorem.

**Theorem 5.3.** For $m \geq 1$, let $x_0^{(m)} = -1$, $x_{m+1}^{(m)} = 1$ and let $x_j^{(m)}$, $j = 1, 2, \ldots, m$ be the zeros of $W_m(x)$ arranged such that $x_j^{(m)} < x_{j+1}^{(m)}$, $j = 1, 2, \ldots, m - 1$. Then in any of the intervals $(x_j^{(m)}, x_{j+1}^{(m)})$, $j = 0, 1, \ldots, m$, there is a zero of $W_{2m_r}$, where $m_r = [(m + 2r)/2]$ with $r \geq 1$. In particular, there holds the interlacing property

$$
x_1^{(2n)} < x_1^{(2n-1)} < x_2^{(2n)} < \cdots < x_{2n-1}^{(2n)} < x_{2n-1}^{(2n-1)} < x_{2n-1}^{(2n)}, \quad n \geq 1.
$$

**Proof.** From Corollary 4.1.1 and from the first quadrature rule in Theorem 5.2

$$
0 = \int_{-1}^{1} W_m(x) F_{m-1}(x) \, d\psi(x)
$$

$$
= \sum_{k=1}^{2m_r} \frac{\lambda_k^{(2m_r)}}{\sqrt{1 - (x_k^{(2m_r)})^2}} W_m(x_k^{(2m_r)}) F_{m-1}(x_k^{(2m_r)}),
$$

where $F_{m-1} \in \Omega_{m-1}$. Now suppose that the sequence $\{W_m(x_1^{(2m_r)}), W_m(x_2^{(2m_r)}), \ldots, W_m(x_{m_r}^{(2m_r)})\}$, obtained from the evaluations of $W_m$ at the points $x_1^{(2m_r)}, x_2^{(2m_r)}, \ldots, x_{m_r}^{(2m_r)}$, has $\ell$ ($< m$) sign changes. Let $y_1, y_2, \ldots, y_\ell$ be points chosen within each of the intervals where the sign changes occur and let $z_j = e^{i2\arccos(y_j)}$, $j = 1, 2, \ldots, \ell$. Hence, if we choose $F_{m-1}$ such that

$$
F_{m-1}(x) = e^{-i(m-1)\theta/2} e^{i(m-1)\pi/2} (z_1 z_2 \cdots z_\ell)^{-1/2} (e^{i\theta} - 1)^{(m-1)-\ell} \prod_{j=1}^{\ell} (e^{i\theta} - z_j),
$$

where $x = \cos(\theta/2)$, then the right-hand side of the quadrature sum in (5.3) cannot be zero (because all the terms are of the same sign). Thus $\ell < m$ leads to a contradiction in (5.3). Hence, considering also that $W_m(x)$ has exactly $m$ zeros in $(-1, 1)$, we must have exactly $m$ sign changes in the sequence $\{W_m(x_1^{(2m_r)}), W_m(x_2^{(2m_r)}), \ldots, W_m(x_{m_r}^{(2m_r)})\}$. The first part of the above theorem is a consequence of this.

To arrive at the latter part of the theorem, we take $m = 2n - 1$ and $r = 1$. \(\square\)
6. Connection with orthogonal polynomials on the unit circle

From now on let \( \psi \) be a positive measure on \([-1, 1]\) such that \( \int_{-1}^{1} (1-x^2)^{-1/2} d\psi(x) \) exists. Let \( \mu \) be a positive measure on the unit circle that satisfies
\[
\int_{\mathbb{C}} f(z) \, d\tilde{\mu}(z) = \int_{\mathbb{C}} f(z) \, d\mu(z) + \delta \, f(1),
\]
where \( \delta \) is some nonzero constant, then (6.1) also holds for \( \tilde{\mu} \).

Now consider the sequence of self-inversive polynomials \( \{\hat{K}_m\} \) given by
\[
e^{-im\theta/2} \hat{K}_m(e^{i\theta}) = 2^m \hat{W}_m(x), \quad m \geq 0,
\]
where \( \{\hat{W}_m\} \) are the normalized orthogonal functions given in Theorem 4.4. Hence, one easily obtains from Corollary 4.1.3 and Theorem 4.4 the following.

**Theorem 6.1.** Elements of the sequence of polynomials \( \{\hat{K}_m\} \) satisfy
\[
\int_{\mathbb{C}} z^{-m+s} \hat{K}_m(z) \, (1-z) \, d\mu(z) = 0, \quad s = 0, 1, \ldots, m-1, \quad m \geq 1.
\]
Moreover,
\[
\hat{K}_0(z) = 1, \quad \hat{K}_1(z) = (1 + i\hat{\beta}_1)z + (1 - i\hat{\beta}_1),
\]
(6.2)
\[
\hat{K}_{m+1}(z) = [(1 + i\hat{\beta}_{m+1})z + (1 - i\hat{\beta}_{m+1})] \hat{K}_m(z) - 4\hat{\alpha}_{m+1} z \hat{K}_{m-1}(z), \quad m \geq 1,
\]
where \( \hat{\beta}_m, \hat{\alpha}_{m+1}, m \geq 1 \) are as in Theorem 4.4.

The remaining results in this section, stated mainly without any proofs, follows from recent results obtained in [5].

The polynomials \( \hat{K}_m, m \geq 0, \) are constant multiples of the CD kernels
\[
\mathcal{K}_m(z, 1) = \frac{s_{m+1}(1)}{1-z} \frac{s_{m+1}(z)}{1-z} - \frac{s_{m+1}(z)}{1-z} = \sum_{j=0}^{m} s_j(1) s_j(z), \quad m \geq 0,
\]
where \( s_m, m \geq 0, \) are the orthonormal polynomials on the unit circle with respect to the positive measure \( \mu \). Orthogonal polynomials on the unit circle (OPUC) were introduced by Gábor Szegő in the first half of the 20th century. Many details regarding the earlier research on these polynomials can be found, for example, in the texts [9], [11], [19] and [20]. For recent and more up to date texts on this subject we refer to the two volumes of Simon [16] and [17]. There is also a nice chapter about these polynomials in Ismail [12].

Now the following result can be stated for the coefficients \( \{\hat{\alpha}_{m+1}\}_m^{\infty} \) that appear in the three term recurrence formula given in Theorem 4.4 (and also in the three term recurrence formula given in Theorem 6.1).

**Theorem 6.2.** Let the positive measure \( \psi \) on \([-1, 1]\) be such that the integral \( \int_{-1}^{1} (1-x^2)^{-1/2} d\psi(x) \) exists. Then the sequence of positive numbers \( \{\hat{\alpha}_{m+1}\}_m^{\infty} \) in Theorem 4.4 is a positive chain sequence. Moreover, this positive chain sequence
is such that its maximal parameter sequence does not coincide with its minimal parameter sequence.

In (see [7]) the knowledge of \( \{\hat{\alpha}_{m+1}\}_{m=1}^{\infty} \) being a positive chain sequence is used, together with (6.2), to prove the interlacing of the zeros of \( \mathcal{W}_m \) and \( \mathcal{W}_{m+1} \) (see [7]). Observe that Theorem 5.3 in the present paper gives only a partial interlacing property.

The results of the above theorem may be true even without the assumed condition for the measure \( \psi \). However, we have not been able to verify this.

Even though the polynomials \( \tilde{K}_m \) are uniquely defined in terms of the measure \( \psi \), we have already observed that the measure \( \mu \) that satisfies (6.1) is not unique (varying according to the size of the jump at \( z = 1 \)). Hence, with such distinct measures there exist distinct sets of OPUC. However, with \( 0 \leq t < 1 \), if one defines the probability measure \( \mu^{(t)} \) such that

\[
-\sin^2(\theta/2) \, d\mu^{(t)}(e^{i\theta}) = c(t) \, d\psi(x),
\]

(6.3)

\( \mu^{(t)} \) has a jump at \( z = 1 \) (i.e. \( \mu^{(t)} \) has a pure point of size \( t \) at \( z = 1 \)),

where \( x = (z^{1/2} + z^{-1/2})/2 = \cos(\theta/2) \) and \( c(t) \) is the normalizing constant so that \( \int_{c} d\mu^{(t)}(z) = 1 \), then we can say more about the associated monic OPUC \( S_n^{(t)} \) and hence, also the orthonormal polynomials \( s_n^{(t)} \).

Let \( \{M_m\}_{m=1}^{\infty} \) be the maximal parameter sequence of the positive chain sequence \( \{\hat{\alpha}_m\}_{m=2}^{\infty} \). Using the value of \( t \) and the sequence \( \{M_m\}_{m=1}^{\infty} \), we now consider the new positive chain sequence \( \{\tilde{\alpha}_m\}_{m=1}^{\infty} \) given by

\[
\tilde{\alpha}_1 = (1 - t)M_1, \quad \tilde{\alpha}_{m+1} = \tilde{\alpha}_{m+1} = (1 - M_m)M_{m+1}, \quad m \geq 1.
\]

It is easily verified (see [4]) that the maximal parameter sequence of the positive chain sequence \( \{\tilde{\alpha}_m\}_{m=1}^{\infty} \) is precisely \( \{M_m\}_{m=0}^{\infty} \), with \( M_0 = t \). Let \( \{m^{(t)}_m\}_{m=0}^{\infty} \) be the minimal parameter sequence of \( \{\tilde{\alpha}_m\}_{m=1}^{\infty} \). That is,

\[
m^{(t)}_0 = 0, \quad m^{(t)}_1 = \tilde{\alpha}_1 = (1 - t)M_1, \quad m^{(t)}_{m+1} = \tilde{\alpha}_{m+1}/(1 - m^{(t)}_m), \quad m \geq 1.
\]

Then we can state the following.

**Theorem 6.3.** Let \( S_n^{(t)}, \ n \geq 0, \) be the monic OPUC with respect to the measure \( \mu^{(t)} \) given by (6.3). Then the associated Verblunsky coefficients \( a^{(t)}_{m-1} = -S^{(t)}_m(0), \ m \geq 1, \) satisfy

\[
a^{(t)}_{m-1} = \frac{1}{\tau_{m-1}} \frac{1 - 2m^{(t)}_m - i\beta_m}{1 - i\beta_m} \quad m \geq 1,
\]

where \( \tau_0 = 1 \) and \( \tau_m = \frac{1 - i\beta_m}{1 + i\beta_m} \tau_{m-1}, \ m \geq 1. \)

7. Examples

Given any measure \( \psi \) on \([-1, 1]\), one can easily obtain by numerical computation the coefficients in the three term recurrence formulas in Theorem 4.1 hence, also information about the required orthogonal functions \( \mathcal{W}_m \). However, for two good reasons we like to consider the normalized orthogonal functions \( \tilde{\mathcal{W}}_m \) given by Theorem 4.4 One of these reasons is that when the measure is symmetric then
these functions turn out to be monic polynomials. The other reason is because of the chain sequence property given by Theorem 6.2.

**Example 1.** Let \( d\psi(x) = (1 - x)dx \). We obtain by numerical computation the following values for the first few \( \hat{\alpha}_m \)'s and \( \hat{\beta}_m \)'s in the three term recurrence formula in Theorem 4.4.

<table>
<thead>
<tr>
<th>( m )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{\beta}_m )</td>
<td>-0.424413</td>
<td>-0.302998</td>
<td>-0.239816</td>
<td>-0.200358</td>
<td>-0.173083</td>
<td>-0.152964</td>
</tr>
<tr>
<td>( \hat{\alpha}_m )</td>
<td>0.222958</td>
<td>0.240821</td>
<td>0.245531</td>
<td>0.247399</td>
<td>0.248315</td>
<td></td>
</tr>
</tbody>
</table>

In the two graphs in Figure 1 we give, respectively, plots of the functions \( \hat{\mathcal{W}}_3 \) and \( \hat{\mathcal{W}}_4 \) and plots of the functions \( \hat{\mathcal{W}}_4 \) and \( \hat{\mathcal{W}}_5 \), separated in this way to be able see clearly the interlacing of the zeros as pointed out after Theorem 6.2.

Glancing at the plot of \( \hat{\mathcal{W}}_4 \) it appears as though this function has a zero at the origin. To be precise, the zero is only very near to the origin and the value of this zero is roughly equal to \(-0.0055075\).

The second example we give here is interesting from the point of view of knowing many things explicitly.

**Example 2.** Let \( d\psi(x) = [e^{\frac{\text{arccos}(x)}{2}}]^{2\eta} \left[ 1 - x^2 \right]^{\lambda-1} dx \), where \( \eta, \lambda \in \mathbb{R} \) and \( \lambda > 1/2 \). Here, we assume \( \text{arccos}(x) \) between 0 and \( \pi \). From results given in [8] we have

\[
\hat{\mathcal{W}}_m(x) = 2^{-m} \frac{(2\lambda)^m}{(\lambda)_m} e^{-im\theta/2} \, _2F_1(-m, b; b + \bar{b}; 1 - e^{i\theta}),
\]

where \( x = \cos(\theta/2), b = \lambda + i\eta \) and the hypergeometric polynomial \(_2F_1(-m, b; b + \bar{b}; 1 - z)\) is self-inversive. The orthogonality of \( \{\hat{\mathcal{W}}_m\} \) can be explicitly written as

\[
\int_{-1}^{1} \hat{\mathcal{W}}_{2n}(x) \hat{\mathcal{W}}_{2m}(x) [e^{-\text{arccos}(x)}]^{2\eta} \left[ 1 - x^2 \right]^{\lambda-1/2} dx = \hat{\rho}_{2m} \delta_{n,m},
\]

\[
\int_{-1}^{1} \hat{\mathcal{W}}_{2n+1}(x) \hat{\mathcal{W}}_{2m+1}(x) [e^{-\text{arccos}(x)}]^{2\eta} \left[ 1 - x^2 \right]^{\lambda-1/2} dx = \hat{\rho}_{2m+1} \delta_{n,m},
\]

\[
\int_{-1}^{1} \hat{\mathcal{W}}_{2n+1}(x) \hat{\mathcal{W}}_{2m}(x) [e^{-\text{arccos}(x)}]^{2\eta} \left[ 1 - x^2 \right]^{\lambda-1} dx = 0,
\]

for \( n, m = 0, 1, 2, \ldots \), where

\[
\hat{\rho}_m = \frac{\pi m! (\lambda + m) \Gamma(2\lambda + m)}{2^{2\lambda+2m-1} e^{\eta \pi} |\Gamma(b + m + 1)|^2 [(\lambda)_m]^2 \left[ (Re([b]_m))^2 + (Im([b]_m))^2 \right]}.
\]
Here, $\Gamma$ represents the gamma function and that $(b)_0 = 1$ and $(b)_m = b(b + 1) \cdots (b + m - 1)$ for $m \geq 1$ are the Pochhammer symbols.

Moreover, in the three term recurrence formula (see Theorem 4.4) for $\{\hat{W}_m\}$,

$$\hat{\beta}_m = \frac{\eta}{m + \lambda - 1} \quad \text{and} \quad \hat{\alpha}_{m+1} = \frac{1}{4} \frac{m(m+2\lambda-1)}{(m+\lambda-1)(m+\lambda)}, \quad m \geq 1.$$

Observe that when $\eta = 0$, the functions $\hat{W}_m$ reduce to the monic ultraspherical polynomials $C_m^{\lambda-1/2}$.

References


Departamento de Matemática Aplicada, IBILCE, UNESP - Universidade Estadual Paulista, 15054-000, São José do Rio Preto, SP, Brazil

E-mail address: cleonice@ibilce.unesp.br

Department of Applied Mathematics, School of Mathematics, University of St. Andrews, Scotland

E-mail address: jhm@st-and.ac.uk

Departamento de Matemática Aplicada, Universidad de Granada, 18071 Granada, Spain

E-mail address: tperez@ugr.es

Departamento de Matemática Aplicada, IBILCE, UNESP - Universidade Estadual Paulista, 15054-000, São José do Rio Preto, SP, Brazil

E-mail address: ranga@ibilce.unesp.br