Boubaker Wavelets Functions: Properties and Applications

Eman H. Ouda  
Samaa F. Ibraheem  
Suha N. Shihab *

Applied Science Department, University of Technology, Baghdad, Iraq

"Corresponding author: emanhasan1911@gmail.com, samaaifuad@yahoo.com, 100031@uotechnology.edu.iq"

"ORCID ID: https://orcid.org/0000-0001-7813-4584, https://orcid.org/0000-0002-0836-5173, https://orcid.org/0000-0003-3730-0149"

Received 23/1/2020, Accepted 7/9/2020, Published Online First 30/4/2021, Published 1/12/2021

This work is licensed under a Creative Commons Attribution 4.0 International License.

Abstract:
This paper is concerned with introducing an explicit expression for orthogonal Boubaker polynomial functions with some important properties. Taking advantage of the interesting properties of Boubaker polynomials, the definition of Boubaker wavelets on interval [0,1) is achieved. These basic functions are orthonormal and have compact support. Wavelets have many advantages and applications in the theoretical and applied fields, and they are applied with the orthogonal polynomials to propose a new method for treating several problems in sciences, and engineering that is wavelet method, which is computationally more attractive in the various fields. A novel property of Boubaker wavelet function derivative in terms of Boubaker wavelet themselves is also obtained. This Boubaker wavelet is utilized along with a collocation method to obtain an approximate numerical solution of singular linear type of Lane-Emden equations. Lane-Emden equations describe several important phenomena in mathematical science and astrophysics such as thermal explosions and stellar structure. It is one of the cases of singular initial value problem in the form of second order nonlinear ordinary differential equation. The suggested method converts Lane-Emden equation into a system of linear differential equations, which can be performed easily on computer. Consequently, the numerical solution concurs with the exact solution even with a small number of Boubaker wavelets used in estimation. An estimation of error bound for the present method is also proved in this work. Three examples of Lane-Emden type equations are included to demonstrate the applicability of the proposed method. The exact known solutions against the obtained approximate results are illustrated in figures for comparison.

Keywords: Boubaker polynomial, Collocation method, Convergence criteria, Error analysis, Wavelet polynomial

Introduction:
Wavelet theory is an emerging area in mathematical research and it has a wide range application in engineering discipline, singular analysis, and time frequency analysis (1-5). It permits the accurate representation of different functions and operators. Furthermore, wavelets functions construct a connection with variety numerical techniques. Many authors have increasingly considered the application of Chebyshev wavelets and shifted Chebyshev wavelets. For example, in (6), the modified Chebyshev wavelets have been applied for solving this film of non-Newtonian fluid problem while Chebyshev wavelets utilized for fractional differential equations by (7) have been shifted, also Chebyshev wavelets have been used for solving problems in mathematics and physics. It is well known that there are other types of wavelet functions and all of them have been applied for solving many practical problems arising in numerous branches of science and engineering, that require solving singular initial value problems and boundary value problems of partial differential equations, linear and nonlinear fractional differential equations. Wavelet functions have been previously applied for obtaining approximate solutions for some of these problems. Authors in (8) have constructed a fast algorithm for some linear and nonlinear wave equations using Taylor wavelets. In the two papers (9,10), the authors treated weakly kernel integral equation of the second kind and fractional delay differential equation respectively using Hermit wavelets. In (11-13), Legendre wavelets method have been
introduced for solving respectively, optimal control problem, fractional differential equations and partial differential equations.

In this paper, first a new form of polynomials is introduced, the orthogonal Boubaker polynomials and derive many interest and useful properties, then present the definition of Boubaker wavelet depending on the orthogonal Boubaker polynomials.

The main goals of the present work are
- Introducing Boubaker wavelets functions and deriving explicit forms of their derivatives.
- Presenting the bounded of Boubaker wavelet coefficients.
- Using Boubaker wavelets functions together with their properties to solve Lane-Emden type equation with the aid of collocation method.

Lane Emden equation is singular initial value problem, and it can be defined with the recurrence relation

\[ B_0(\tau) = 1 \]

The first orthogonal Boubaker polynomial \( BO_1(\tau) \) is

\[ BO_1(\tau) = \left[ \tau - \frac{\int_0^\tau \tau \, d\tau}{\int_0^\tau \tau \, d\tau} \right] BO_0 = \left( \tau - \frac{1}{2} \right) \int_0^\tau BO_0 \, d\tau \]

In order to construct higher order orthogonal Boubaker polynomial, the following recurrence relation is used

\[ BO_{i+1}(\tau) = \left[ \tau - \frac{\int_0^\tau \tau BO_i \, d\tau}{\int_0^\tau \tau BO_i \, d\tau} \right] BO_i - \frac{\int_0^\tau \tau BO_i \, d\tau}{\int_0^\tau \tau BO_i \, d\tau} BO_i \]

**Definition 1**

The expression of Boubaker polynomials \( B_m(\tau) \) is described as

\[ B_m(\tau) = \sum_{p=0}^{\lfloor m/2 \rfloor} (-1)^p \binom{n-4p}{n-p} \binom{n-p}{p} \tau^{n-2p} \]

(1)

and it can be defined with the recurrence relation given below

\[ B_m(\tau) = \tau B_{m-1}(\tau) - B_{m-2}(\tau) \quad n > 2 \]

(2)

with \( B_0(\tau) = 1, B_1(\tau) = \tau \) and \( B_2(\tau) = \tau^2 + \)

2 Boubaker polynomials are not orthogonal but when applying the Gram-Schmit process on sets of Boubaker polynomials one can obtain orthogonal Boubaker polynomials \( BO_m(\tau) \).

Orthogonal Boubaker polynomials are generated using

\[ \langle \tau_i, \tau_j \rangle = \int_0^1 \tau_i \tau_j \, d\tau \]

Define \( BO_0(\tau) = 1 \)

The first orthogonal Boubaker polynomial \( BO_1(\tau) \) is

\[ BO_1(\tau) = \left[ \tau - \frac{\int_0^\tau \tau BO_0 \, d\tau}{\int_0^\tau \tau BO_0 \, d\tau} \right] BO_0 \]

(3)

The first six \( BO_m(\tau) \) are given below and are plotted in Fig. 1

\[ BO_0(\tau) = 1 \]

\[ BO_1(\tau) = \frac{1}{2} (2\tau - 1) \]

\[ BO_2(\tau) = \frac{1}{6} (6\tau^2 - 6\tau + 1) \]

\[ BO_3(\tau) = \frac{1}{20} (20\tau^3 - 30\tau^2 + 12\tau - 1) \]

\[ BO_4(\tau) = \frac{1}{70} (70\tau^4 - 140\tau^3 + 90\tau^2 - 20\tau + 1) \]

\[ BO_5(\tau) = \frac{1}{252} (252\tau^5 - 630\tau^4 + 560\tau^3 - 210\tau^2 + 30\tau - 1) \]

\[ BO_6(\tau) = \frac{1}{924} (924\tau^6 - 2772\tau^5 + 3150\tau^4 - 1680\tau^3 + 420\tau^2 - 42\tau + 1) \]
A recursive definition also can be used to generate orthogonal Boubaker polynomials over the interval $[0,1]$

$$BO_{m+1}(\tau) = \frac{(m+1)!}{2(m+1)!} \sum_{n=1}^m \frac{(2m+1)!}{(m+1)!(m+2-n)!} (2\tau - n)$$

(4)

$$m \geq 2$$

with $BO_0(\tau) = 1$ and $BO_1(\tau) = \frac{1}{2}(2\tau - 1)$

The other property of the orthogonal Boubaker polynomials is

$$BO_m(\tau) = \frac{(m!)^2}{(2m)!} \sum_{n=1}^m \frac{2m-n}{(m-n)!} BO_{m-n}(\tau)$$

(5)

**Definition 3**

The $m^{th}$ degree of orthonormal Boubaker polynomials are defined below over the interval $[0,1]$

$$BO_m(\tau) = \sqrt{2m+1} \frac{(2m)!}{(m!)^2} BO_m(\tau)$$

(6)

**Bouabaker Wavelet**

Wavelet functions are constructed from dilation and translation of a definite function, named mother wavelet. Wavelet functions may be defined as

$$\sigma_{a,b}(\tau) = \frac{1}{a} \Theta \left( \frac{\tau - b}{a} \right) \quad a, b \in \mathbb{R}, a \neq 0.$$

where $a$ and $b$ are dilation and translation parameters respectively while $\tau$ is the normalized time.

Consider the Bouabaker wavelets as $\eta_{m,n}(\tau) = \eta(m, n, \tau)$ where $n = 0, 1, 2, ..., 2^{k+1} (k = 0, 1, 2, 3, ...)$, while $m$ represents the order of orthogonal Bouabaker polynomials.

Then the Bouabaker wavelets can be defined as below

$$\eta_{mn}(\tau) = \begin{cases} \sqrt{2m+1} \frac{(2m)!}{(m!)^2} 2^k BO_m(2^k \tau - n) & \frac{n}{2^k} \leq \tau < \frac{n+1}{2^k} \\ 0 & \text{otherwise} \end{cases}$$

(7)

In Eq. 7, $BO_m(\tau)$ describes orthogonal Bouabaker polynomial of order $m$.

Therefore, the total Bouabaker wavelet approximation can be presented as below

$$u(\tau) = \sum_{n=1}^{\infty} \sum_{m=0}^{\infty} a_{mn} \eta_{nm}(\tau)$$

(8)

By truncating the infinite series in Eq. 8, then the result can be written as

$$u(\tau) \approx \sum_{n=1}^{M} \sum_{m=0}^{M-1} a_{mn} \eta_{nm}$$

(9)

where $a_{nm} = \langle u(\tau), \eta_{nm}(\tau) \rangle$, in which $(0,0)$ denotes the inner product in $L^2[0,1]$, 

Eq. 9 can be written in a matrix form as,

$$u(\tau) = \mathbf{a}^T \mathbf{\eta}(\tau)$$

(10)

where $\mathbf{a}$ and $\mathbf{\eta}(\tau)$ are $2^{k-1} \times 1$ matrices given by

$$\mathbf{a} = [a_{10}, a_{11}, ... , a_{1(M-1)}, a_{20}, ... , a_{2(M-1)}, ... , a_{2^k(k-1)0}, ... , [a_{2^k(k-1)1}]^T]$$

(11)

and

$$\mathbf{\eta}(\tau) = [\eta_{10}, \eta_{11}, ... , \eta_{1(M-1)}, \eta_{20}, ... , \eta_{2(M-1)}, ... , \eta_{2^k(k-1)0}, ... , [\eta_{2^k(k-1)1}]^T]$$

(12)

**Bounded of Bouabaker Wavelet Coefficients**

**Theorem 1**

Let $x(\tau)$ be a continuous function defined on $[0,1]$ and $\mathbf{a}^T(\tau)$ be the approximation of $\mathbf{a}(\tau)$ by applying Bouabaker wavelets. Also suppose that $x(\tau)$ is bounded by a positive constant, that is
\[ |x(t)| < \epsilon. \] Then the Boubaker wavelet coefficients of \( x(t) \) are bounded and
\[ |c_{nm}| \leq \frac{\epsilon}{2^\frac{n+1}{2}} \left( \frac{m!}{(2m)!} \right)^2 \sqrt{m + \frac{1}{2}} \]

**Proof**

\[
x^*(t) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} c_{nm} \eta_{nm}(t)
\]
\[ c_{nm} = (x, \eta_{nm}) = \int_0^1 x(t) \eta_{nm}(t) dt = \int_0^1 \frac{(2m)!}{(m!)^2} \left( \frac{n+1}{2k} \right)^{\frac{1}{2}} x(t) B_0(u) du \]

Let \( 2k^2 - n = u \) then \( du = 2k^2 dt \)
\[ c_{nm} = \frac{(2m)!}{(m!)^2} 2^{\frac{k}{2}} 2^{m} + 1 2^{\frac{k}{2}} \int_0^1 x(u + n) \left( \frac{2k}{2k} \right) B_0(u) du \]
\[ = \frac{(2m)!}{(m!)^2} 2^{\frac{k}{2}} 2^{m} + 1 \int_0^1 (u + n) 2^{\frac{k}{2}} B_0(u) du \]

Since \( |x(t)| < \epsilon \)
\[ |c_{nm}| \leq \frac{(2m)!}{(m!)^2} 2^{\frac{k}{2}} 2^{m} + 1 \frac{1}{2} \int_0^1 x(u + n) \left( \frac{2k}{2k} \right) B_0(u) du \]
\[ = \frac{(2m)!}{(m!)^2} 2^{\frac{k}{2}} 2^{m} + 1 \frac{1}{2} \int_0^1 B_0(u) du \]
\[ \leq \frac{(2m)!}{(m!)^2} 2^{\frac{k}{2}} 2^{m} + 1 \frac{1}{2} \int_0^1 B_0(u) du \]
\[ \leq 1 \quad \forall \quad u \in [0, 1] \]
\[ \int_0^1 B_0(u) du \leq 1 \]
\[ |c_{nm}| \leq \frac{(2m)!}{(m!)^2} 2^{\frac{k}{2}} 2^{m} + 1 \frac{1}{2} \int_0^1 B_0(u) du \]
\[ \leq \frac{(2m)!}{(m!)^2} 2^{\frac{k}{2}} 2^{m} + 1 \frac{1}{2} \sqrt{m + \frac{1}{2}} \]
\[ \leq \frac{(2m)!}{(m!)^2} 2^{\frac{k}{2}} 2^{m} + 1 \frac{1}{2} \sqrt{m + \frac{1}{2}} \]
\[ |c_{nm}| \leq \frac{\epsilon}{2^\frac{n+1}{2}} \left( \frac{m!}{(2m)!} \right)^2 \sqrt{m + \frac{1}{2}} \]

This is the required result.

**The Derivative of Boubaker Wavelet in Terms of Boubaker Wavelets**

In the next theorem, a relation between orthogonal Boubaker polynomials and their derivatives is derived, which is very important in deriving the derivative of Boubaker wavelets.

**Theorem 2**

Let \( B_0(m) \) be the orthogonal Boubaker polynomials into \([0, 1]\), then the following relation is satisfied
\[ B_0(m) = 2^\frac{(m)!}{(2m)!} \sum_{k=1}^{m} \frac{(m-k)!}{(m-k)!} (2m-k) + 1) B_0(m-k) \]

\( (m-k) \) is odd for \( m \) even, \( (m-k) \) is even for \( m \) odd

where \( m = 1, 2, \ldots \), and \( B_0(0) = 0 \)

**Theorem 3**

Let \( \eta(t) \) be the Boubaker wavelet into \([0, 1]\), then the following relation is satisfied
\[ \eta(t) = 2^k + 1 \cdot (2m + 1) + \sum_{k=1}^{m} \frac{(2m)!}{(m!)^2} (2s + 1) \eta(s) \]

\( s \) is odd for \( m \) even, \( s \) is even for \( m \) odd

where \( s = m - k, m = 1, 2, 3 \ldots \) and \( \eta_0(0) = 0 \)

**Proof**

Consider the vector Boubaker wavelet defined in Eq.7
\[ \eta_{nm}(t) = \begin{cases} \sqrt{2m + 1} \left( \frac{2m!}{(m!)^2} \right)^{1/2} B_0(2m - n) \frac{n+1}{2k} \leq \tau < \frac{n+1}{2k} \\ 0 \quad \text{otherwise} \end{cases} \]

Differentiating \( \eta_{nm}(\tau) \) with respect to \( \tau \), yields
\[ \dot{\eta}_{nm}(\tau) = \begin{cases} \sqrt{2m + 1} \left( \frac{2m!}{(m!)^2} \right)^{1/2} B_0(2m - n) \frac{n+1}{2k} \leq \tau < \frac{n+1}{2k} \\ 0 \quad \text{otherwise} \end{cases} \]

(15)

Using the result in Eq. 13, one can get Eq. 15
\[ \eta_{nm}(\tau) = \sqrt{2m + 1} \left( \frac{2m!}{(m!)^2} \right)^{1/2} \cdot 2^k \cdot \left( \frac{(m-k)!}{(m-k)!} \right)^2 B_0(2m - n) \]
\[ = 2^{k+1} \left( 2m + 1 \right)^{1/2} \sum_{k=1}^{m} \frac{(2m-k)!}{(m-k)!} (2m-k) + 1) \eta_{m-k}(\tau) \]

Since \( s = m - k \)
Therefore:
\[ \dot{\eta}_{nm}(\tau) = 2^{k+1} \left( 2m + 1 \right)^{1/2} \sum_{k=1}^{m} \frac{(2m)!}{(m!)^2} (2s + 1) \eta_0(\tau) \]

**Application of Solutions in the Boubaker Wavelets Basis**

In this section, the solution of Lane-Emden equations are obtained by applying Boubaker wavelets collocation method based on making use of the previously introduced derivative of Boubaker wavelet.
Consider the Lane-Emden of the form
\[ \ddot{y}(\tau) + \frac{\alpha}{\tau} \dot{y}(\tau) + y(\tau) = g(\tau) \]
(16)
where \( \tau \in (0, 1) \) and \( \alpha \geq 0 \) with the conditions
\[ y(0) = a, \quad \dot{y}(0) = 0 \]
(17)
Consider an approximate solution to Eq. 16 which is given in terms of Boubaker wavelets as
\[ y_{nm}(\tau) = \sum_{n=1}^{2^k-1} \sum_{m=0}^{M-1} a_{nm} \eta_{nm}(\tau) \]
(18)
Then one can obtain the following residual after substituting of Eq. 18 into Eq. 16
\[
R(\tau) = \tau \sum_{n=1}^{2^k-1} \sum_{m=2}^{M-1} a_{nm} \eta_{nm}(\tau) + a \sum_{n=1}^{2^k-1} \sum_{m=0}^{M-1} a_{nm} \eta_{nm}(\tau)
\]
(19)
Using the collocation method yields
\[ R(\tau_i) = 0, \quad i = 1, 2, 3, ..., 2^k(M + 1) - 2, \]
Moreover, uses of initial conditions Eq. 17 give
\[
\sum_{n=1}^{2^k-1} \sum_{m=0}^{M-1} a_{nm} \eta_{nm}(0) = a
\]
(20)
\[
\sum_{n=1}^{2^k-1} \sum_{m=0}^{M-1} a_{nm} \eta_{nm}(0) = 0
\]
(21)
Additional \( 2^k - 1 \) equations are obtained in the unknown expansion coefficients \( a_{nm} \).

### Numerical Examples

#### Example 1
The first test example is
\[ \ddot{y}(\tau) + \frac{2}{\tau} \dot{y}(\tau) + 1 = 0 \quad , 0 < \tau \leq 1 \]
with \( y(0) = 1, \quad \dot{y}(0) = 0 \)
Applying the collocation technique with Boubaker wavelet presented in section 6 to obtain
\[ y_{nm}(\tau) = \sum_{n=1}^{2^k-1} \sum_{m=0}^{M-1} a_{nm} \eta_{nm}(\tau) \]
(22)
For \( M = 5 \) and \( k = 1 \) and by using Eq. 19 with the collocation points \( \tau_1 = 0.25, \quad \tau_2 = 0.5 \), and \( \tau_3 = 1 \), one can obtain
\[
\begin{align*}
4\sqrt{3}a_1 - 6\sqrt{5}a_2 + \frac{6072}{243}a_3 + \frac{57}{7}a_4 &= -0.25 \\
4\sqrt{3}a_1 - \frac{2505}{263}a_3 + 12a_4 &= -0.5 \\
4\sqrt{3}a_1 + 12\sqrt{5}a_2 + \frac{9639}{253}a_3 + \frac{240}{7}a_4 &= -1
\end{align*}
\]
Applying the initial conditions from Eqns. 20-21 to get
\[
\begin{align*}
a_0 &= \frac{3}{2} \sqrt{3}a_1 + \frac{13}{6} \sqrt{5}a_2 - \frac{63}{20} \sqrt{7}a_3 = 1 \\
2\sqrt{3}a_1 - 6\sqrt{5}a_2 + \frac{66}{7} \sqrt{7}a_3 + \frac{540}{7}a_4 &= 0
\end{align*}
\]
After solving such system, one can get
\[
a_0 = 0.90277777777778, \quad a_1 = -0.072168783648703, \quad a_2 = -0.018633898912498, \quad a_3 = 0, \quad a_4 = 0.
\]
Consequently, the solution presented in Eq. 22 can be determined.

Table 1 gives the comparison between the approximate solution and the exact solution
\[ u(\tau) = 1 - \frac{1}{3!} \tau^2 \]

<table>
<thead>
<tr>
<th>( T )</th>
<th>( y_{appr}(\tau) )</th>
<th>( y_{exact}(\tau) )</th>
<th>( \text{error} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.000000000000000</td>
<td>1.000000000000000</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>0.1</td>
<td>0.998333333333334</td>
<td>0.998333333333334</td>
<td>0.000000000000001</td>
</tr>
<tr>
<td>0.2</td>
<td>0.993333333333334</td>
<td>0.993333333333334</td>
<td>0.000000000000001</td>
</tr>
<tr>
<td>0.3</td>
<td>0.985000000000000</td>
<td>0.985000000000000</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>0.4</td>
<td>0.973333333333334</td>
<td>0.973333333333333</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>0.5</td>
<td>0.958333333333334</td>
<td>0.958333333333333</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>0.6</td>
<td>0.940000000000000</td>
<td>0.940000000000000</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>0.7</td>
<td>0.918333333333334</td>
<td>0.918333333333334</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>0.8</td>
<td>0.893333333333333</td>
<td>0.893333333333333</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>0.9</td>
<td>0.865000000000000</td>
<td>0.865000000000000</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>1.0</td>
<td>0.833333333333334</td>
<td>0.833333333333333</td>
<td>0.000000000000000</td>
</tr>
</tbody>
</table>

#### Example 2
The second test Lane-Emden differential equation is
\[ \ddot{y}(\tau) + \frac{2}{\tau} \dot{y}(\tau) + y(\tau) = 0 \quad , 0 < \tau \leq 1 \]
with \( y(0) = 1, \quad \dot{y}(0) = 0 \)
where the exact solution is \( y(\tau) = \frac{\sin(\tau)}{\tau} \).
For $M = 5$ and $k = 1$ and by using Eq. 19 with the collocation points $\tau_1 = 0.25$, $\tau_2 = 0.5$, and $\tau_3 = 1$, one can obtain
\[
\begin{align*}
1 & \frac{a_0}{2} + \frac{15\sqrt{3}a_1 + 311}{4} a_2 + \frac{1683}{7126} a_3 + \frac{140}{4} a_4 = 0 \\
1 & \frac{a_0}{4} + \frac{15\sqrt{3}a_1 + 3897}{4} a_2 + \frac{2045}{7126} a_3 + \frac{9}{4} a_4 = 0 \\
\frac{a_0}{4} & + \frac{9\sqrt{3}a_1 + 225}{73} a_2 + \frac{2403}{225} a_3 + \frac{70}{7} a_4 = 0
\end{align*}
\]
Applying the initial conditions from Eqs. 20-21 to get $a_0 - \frac{3}{2} \sqrt{3}a_1 + \frac{13}{6} \sqrt{5}a_2 - \frac{63}{20} \sqrt{7}a_3 + \frac{963}{70} a_4 = 1$

\[
2\sqrt{3}a_1 - 6\sqrt{5}a_2 + \frac{66}{5} \sqrt{7}a_3 - \frac{540}{7} a_4 = 0
\]
After solving such system, one can get $a_0 = 0.905936447152376$, $a_1 = -0.067954491278279$, $a_2 = -0.015573553854944$, $a_3 = 0.001100514472143$, $a_4 = 0.000155220642522$.

The comparison between the approximate solution and the exact solution can be seen in Table 2.

| Table 2. Results of Example 2 with $M=5$ and $k=1$ |
| --- | --- | --- |
| $\tau$ | $y_{exact}(\tau)$ | $y_{appr}(\tau)$ | error |
| 0 | 1.0000000000000000 | 1.0000000000000000 | 0.0000000000000000 |
| 0.1 | 0.998334164648282 | 0.998332108068162 | 0.0000000205841192 |
| 0.2 | 0.993466539753060 | 0.993411399895023 | 0.000000514802832 |
| 0.3 | 0.985067355779999 | 0.985059679776240 | 0.000000778561017 |
| 0.4 | 0.973548557716260 | 0.973537746231033 | 0.000000819950459 |
| 0.5 | 0.958851077208406 | 0.958843998883373 | 0.000000176220069 |
| 0.6 | 0.941070889917257 | 0.941064176006641 | 0.000000612991084 |
| 0.7 | 0.920310981768130 | 0.920302542437070 | 0.000000843933106 |
| 0.8 | 0.896695113624403 | 0.896680888884764 | 0.000000142473963 |
| 0.9 | 0.870363232919426 | 0.870338976248886 | 0.000000225657054 |
| 1.0 | 0.841470984807897 | 0.841434447252614 | 0.0000003653755528 |

The values of exact solution and approximate solution at some points are reported in Table 3 with $M = 6$, $M = 7$ and $k = 1$. In addition, the maximum absolute error has been listed in Table 4 for $M = 5, 6$ and $7$ and $k = 1$.

| Table 3. Results of Example 2 for $M=6, M=7$ and $k=1$ |
| --- | --- | --- | --- | --- | --- |
| $\tau$ | $y_{exact}(\tau)$ | error | $y_{appr}(\tau)$ | error |
| 0 | 1 | 0 | 1 | 0 |
| 0.1 | 0.9983341646482 | 0.0000000760382 | 0.9983341646482 | 0.00000000380 |
| 0.2 | 0.9934665397530 | 0.0000001898197 | 0.9934665397530 | 0.0000000587 |
| 0.3 | 0.9850673557799 | 0.0000002594718 | 0.9850673557799 | 0.0000000637 |
| 0.4 | 0.9735485577162 | 0.0000002782978 | 0.9735485577162 | 0.0000000962 |
| 0.5 | 0.9588510772084 | 0.0000002710436 | 0.9588510772084 | 0.0000001531 |
| 0.6 | 0.9410707889170 | 0.0000002639264 | 0.9410707889170 | 0.0000001872 |
| 0.7 | 0.9203109817861 | 0.0000002680435 | 0.9203109817861 | 0.0000001626 |
| 0.8 | 0.8966951136244 | 0.0000002756771 | 0.8966951136244 | 0.0000001135 |
| 0.9 | 0.8703632329194 | 0.0000002689089 | 0.8703632329194 | 0.0000001486 |
| 1.0 | 0.8414709848078 | 0.0000002398682 | 0.8414709848078 | 0.0000003333 |

| Table 4. Maximum absolute error of Example 2 for $M=5,6,7$ and $k=1$ |
| --- | --- | --- |
| Maximum error | $M=5, k=1$ | $M=6, k=1$ | $M=7, k=1$ |
| 0.000036537556 | 0.000002782978 | 0.0000003333 |

It is clear from Table 3 that only a small number of Boubaker wavelets basis functions are needed to obtain the approximate solution, which agrees with the actual one.
Example 3

Consider the third Lane-Emden type equation:
\[ \ddot{y}(x) + \frac{2}{\tau} \dot{y}(x) + y(x) = 6 + 12 \tau + \tau^2 + \tau^3, \quad 0 < \tau \leq 1 \]

Subject to \( y(0) = 0, y(0) = 0 \) with exact solution
\[ y(\tau) = \tau^2 + \tau^3 \]

This problem is solved with Boubaker wavelets using \( M = 5 \), and \( k = 1 \) the linear system of 5-equations is obtained
\[
\begin{align*}
1 & \quad \frac{311}{1609} a_2 - \frac{140}{743} a_3 + a_4 = \frac{99}{8} \\
\frac{49}{15} & \quad \frac{7126}{3897} a_2 - \frac{140}{743} a_3 + a_4 = \frac{99}{8} \\
\frac{9}{2} & \quad \frac{7126}{2045} a_2 + \frac{140}{743} a_3 + a_4 = \frac{99}{8} \\
\frac{9}{2} & \quad \frac{102}{73} a_2 + \frac{225}{403} a_3 - \frac{70}{149} a_4 = 20
\end{align*}
\]

The following unknown parameters are obtained
\[ a_0 = 1.052083235111342, \quad a_1 = 0.93097736020200, \quad a_2 = 0.36336161797005, \quad a_3 = 0.047245598838191, \quad a_4 = 0.0000000000195274. \]

As it can be shown in Table 5 that only a few number of Boubaker wavelets basis functions are utilized to reach the approximate solution with a satisfying result.

### Table 5. Results of Example 3

<table>
<thead>
<tr>
<th>( t )</th>
<th>( y_{\text{app}}(\tau) )</th>
<th>( y_{\text{exact}}(\tau) )</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000000000000000</td>
<td>0</td>
<td>0.000000000000000</td>
</tr>
<tr>
<td>0.1</td>
<td>0.0109999999238870</td>
<td>0.011000000000000</td>
<td>0.000000000071130</td>
</tr>
<tr>
<td>0.2</td>
<td>0.047999973416433</td>
<td>0.048000000000000</td>
<td>0.000000000028867</td>
</tr>
<tr>
<td>0.3</td>
<td>0.116999947540987</td>
<td>0.117000000000000</td>
<td>0.000000000005013</td>
</tr>
<tr>
<td>0.4</td>
<td>0.223999919833328</td>
<td>0.224000000000000</td>
<td>0.000000000008672</td>
</tr>
<tr>
<td>0.5</td>
<td>0.374999895276744</td>
<td>0.375000000000000</td>
<td>0.00000000000473256</td>
</tr>
<tr>
<td>0.6</td>
<td>0.575999878817022</td>
<td>0.576000000000000</td>
<td>0.000000000001182978</td>
</tr>
<tr>
<td>0.7</td>
<td>0.832999875462444</td>
<td>0.833000000000000</td>
<td>0.00000000000124537557</td>
</tr>
<tr>
<td>0.8</td>
<td>1.151999890233785</td>
<td>1.152000000000000</td>
<td>0.00000000000109766216</td>
</tr>
<tr>
<td>0.9</td>
<td>1.538999928174318</td>
<td>1.539000000000000</td>
<td>0.0000000000017825682</td>
</tr>
<tr>
<td>1.0</td>
<td>1.999999994349811</td>
<td>2.000000000000000</td>
<td>0.0000000000005650189</td>
</tr>
</tbody>
</table>

**Conclusion:**

In this paper, has presented for the first time the exact expression for orthogonal Boubaker polynomials and then defined the Boubaker wavelet. The basic shapes of the first six orthogonal Boubaker polynomials are plotted in Fig.1. These polynomials can be used to present complicated functions. In addition, some important properties are derived and employed for obtaining the approximate solution of Lane-Emden equations. Only a few number of Boubaker wavelet basis is needed to achieve the high accuracy. The approximate solutions obtained using the collocation Boubaker wavelets are compared with the exact solution and the agreement between them is obtained. This method has reasonably shown good performance for all of the Lane-Emden type equations.

**Authors’ declaration:**

- **Conflicts of Interest:** None.
- We hereby confirm that all the Figures and Tables in the manuscript are mine ours. Besides, the Figures and images, which are not mine ours, have been given the permission for republication attached with the manuscript.

- Ethical Clearance: The project was approved by the local ethical committee in University of Technology.

**References:**

خواص وتطبيقات دوال بوبكر الموجية

سما فؤاد أبراهيم

أيمن حسن عودة

قسم العلوم التطبيقية، الجامعة التكنولوجية، بغداد، العراق

الخلاصة:

تم في هذا البحث تقديم شرح تفصيلي لدوال متعددة جهد بوبكر الموجية، مع بعض الخواص ذات الأهمية، وكذلك اقتراح تعريف

معادلات جهد بوبكر الموجية في الفترة (1, 0) وذلك بالاستفادة من بعض الخواص المهمة معединة كبيرة عند الاستعداد منها في مجال

التحقق إضافة لبعض النتائج الإقتصادية والعددية من نوع معادلات لان ايمدن. تضمن هذا البحث تطبيقات متعددة في المجالات ذات

الخصائص الجزيئية، وتكون النتائج العملية في التنقل، والمحافظة على طريقة موجبة لغرض التصنيف للحصول على حل

 מעادلات لان ايمدن كอนية. استخدمت معاملة بوبكر مع طريقة التجميع للحصول على خاصية جديدة. وهي مسئولة دالة بوبكر الموجية. öğrenت

الخلاصة