

QUADRATIC APPROXIMATION OF GENERALIZED TRIBONACCI SEQUENCES

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Abstract

In this paper, we give quadratic approximation of generalized Tribonacci sequence $\{V_n\}_{n \geq 0}$ defined by $V_n = rV_{n-1} + sV_{n-2} + tV_{n-3}$ ($n \geq 3$) and use this result to give the matrix form of the n -th power of a companion matrix of $\{V_n\}_{n \geq 0}$. Then we re-prove the cubic identity or Cassini-type formula for $\{V_n\}_{n \geq 0}$ and the Binet's formula of the generalized Tribonacci quaternions.

Keywords: Binet's formula, companion matrix, generalized Tribonacci sequence, Narayana number, Padovan number, quadratic approximation, Tribonacci number.

2010 Mathematics Subject Classification: Primary: 11B39; Secondary: 15A24, 40C05.

1. INTRODUCTION

Let $Q = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$ be a companion matrix of the Tribonacci sequence $\{T_n\}_{n \geq 0}$ defined by the third-order linear recurrence relation

$$(1) \quad T_0 = T_1 = 0, \quad T_2 = 1, \quad T_n = T_{n-1} + T_{n-2} + T_{n-3} \quad (n \geq 3).$$

Then, by an inductive argument, the n -th power Q^n has the matrix form

$$(2) \quad Q^n = \begin{bmatrix} T_{n+2} & T_{n+1} + T_n & T_{n+1} \\ T_{n+1} & T_n + T_{n-1} & T_n \\ T_n & T_{n-1} + T_{n-2} & T_{n-1} \end{bmatrix} \quad (n \geq 2).$$

For further properties of Tribonacci numbers, we refer to [3, 5, 6].

The property $\det(Q^n) = (\det(Q))^n = 1$ and equation (2) provides an alternate proof of the Cassini-type (or cubic-type) formula for $\{T_n\}_{n \geq 0}$:

$$(3) \quad T_n^3 + T_{n-1}^2 T_{n+2} + T_{n-2} T_{n+1}^2 - 2T_{n-1} T_n T_{n+1} - T_{n-2} T_n T_{n+2} = 1.$$

Now, let's think of the other access method in order to give the matrix form equation (2) of Q^n . This method gives the motivation of our research. That is, our research is based on the following observation. It is well known [11] that the usual Tribonacci numbers can be expressed using Binet's formula

$$(4) \quad T_n = \frac{\alpha^n}{(\alpha - \omega_1)(\alpha - \omega_2)} - \frac{\omega_1^n}{(\alpha - \omega_1)(\omega_1 - \omega_2)} + \frac{\omega_2^n}{(\alpha - \omega_2)(\omega_1 - \omega_2)}.$$

where α , ω_1 and ω_2 are the roots of the cubic equation $x^3 - x^2 - x - 1 = 0$. Furthermore, $\alpha = \frac{1}{3} + A_T + B_T$, $\omega_1 = \frac{1}{3} + \epsilon A_T + \epsilon^2 B_T$ and $\omega_2 = \frac{1}{3} + \epsilon^2 A_T + \epsilon B_T$, where

$$A_T = \sqrt[3]{\frac{19}{27} + \sqrt{\frac{11}{27}}}, \quad B_T = \sqrt[3]{\frac{19}{27} - \sqrt{\frac{11}{27}}}$$

and $\epsilon = -\frac{1}{2} + \frac{i\sqrt{3}}{2}$.

From the Binet's formula equation (4), using the classic identities $\alpha + \omega_1 + \omega_2 = 1$, $\alpha\omega_1 + \alpha\omega_2 + \omega_1\omega_2 = -1$, we have for any integer $n \geq 2$:

$$\begin{aligned} & \alpha T_n + (1 + \omega_1\omega_2)T_{n-1} + T_{n-2} \\ &= \frac{\alpha^{n-2}(\alpha^3 + (1 + \omega_1\omega_2)\alpha + 1)}{(\alpha - \omega_1)(\alpha - \omega_2)} - \frac{\omega_1^{n-2}(\alpha\omega_1^2 + (1 + \omega_1\omega_2)\omega_1 + 1)}{(\alpha - \omega_1)(\omega_1 - \omega_2)} \\ &+ \frac{\omega_2^{n-2}(\alpha\omega_2^2 + (1 + \omega_1\omega_2)\omega_2 + 1)}{(\alpha - \omega_2)(\omega_1 - \omega_2)} = \alpha^{n-1}. \end{aligned}$$

Then, we obtain

$$(5) \quad \alpha T_n + (1 + \omega_1\omega_2)T_{n-1} + T_{n-2} = \alpha^{n-1} \quad (n \geq 2).$$

Multiplying equation (5) by α , using $\alpha\omega_1\omega_2 = 1$, if we then interchange the role of α , and ω_1 and α , and ω_2 , we obtain the quadratic approximation of $\{T_n\}_{n \geq 0}$

$$(6) \quad \text{Quadratic app. of } \{T_n\} : \begin{cases} \alpha^n = T_n \alpha^2 + (T_{n-1} + T_{n-2})\alpha + T_{n-1}, \\ \omega_1^n = T_n \omega_1^2 + (T_{n-1} + T_{n-2})\omega_1 + T_{n-1}, \\ \omega_2^n = T_n \omega_2^2 + (T_{n-1} + T_{n-2})\omega_2 + T_{n-1}, \end{cases}$$

where α , ω_1 and ω_2 are the roots of the cubic equation $x^3 - x^2 - x - 1 = 0$.

In equation (5), if we replace α with the companion matrix Q and change T_{n-1} into the matrix $T_{n-1}I_3$, where I_3 is the 3×3 identity matrix, then we obtain the matrix form equation (2) of Q^n

$$Q^n = T_n Q^2 + (T_{n-1} + T_{n-2})Q + T_{n-1}I_3 \left(= \begin{bmatrix} T_{n+2} & T_{n+1} + T_n & T_{n+1} \\ T_{n+1} & T_n + T_{n-1} & T_n \\ T_n & T_{n-1} + T_{n-2} & T_{n-1} \end{bmatrix} \right).$$

The Tribonacci sequence has been generalized in many ways, for example, by changing the recurrence relation while preserving the initial terms, by altering the initial terms but maintaining the recurrence relation, by combining of these two techniques, and so on (for more details see [4, 8, 10, 12]).

In this paper, we consider one type of generalized Tribonacci sequences. In fact, the sequence $\{V_n\}_{n \geq 0}$ defined by Shannon and Horadam [10] depending on six positive integer parameters V_0, V_1, V_2, r, s and t used in the third-order linear recurrence relation:

$$(7) \quad V_n = rV_{n-1} + sV_{n-2} + tV_{n-3} \quad (n \geq 3).$$

In this paper, as mentioned above, we provide quadratic approximation of $\{V_n\}_{n \geq 0}$ and use this result to give the matrix form of the n -th power of a companion matrix of $\{V_n\}_{n \geq 0}$. Then, we re-prove the Cassini-type formula for the sequence $\{V_n\}_{n \geq 0}$ and Binet's formula of the generalized Tribonacci quaternions.

2. QUADRATIC APPROXIMATION OF THE GENERALIZED TRIBONACCI SEQUENCES $\{V_n\}$

We consider the generalized Tribonacci sequence $\{V_n(V_0, V_1, V_2; r, s, t)\}$, or briefly $\{V_n\}$, defined as in (7), where V_0, V_1, V_2 are arbitrary integers and r, s, t , are real numbers. This sequence has been studied by Shannon and Horadam [10], Yalavigi [13] and Pethe [8]. If we set $r = s = t = 1$ and $V_0 = V_1 = 0, V_2 = 1$, then $\{V_n\}$ is the well-known Tribonacci sequence, and if $r = s = t = 1$ and $V_0 = 3, V_1 = 1, V_2 = 3$, then $\{V_n\}$ is the Tribonacci-Lucas investigated by Elia in [2].

As the elements of this Tribonacci-type number sequence provide third order iterative relation, its characteristic equation is $x^3 - rx^2 - sx - t = 0$, whose roots are $\alpha = \alpha(r, s, t) = \frac{r}{3} + A_V + B_V, \omega_1 = \frac{r}{3} + \epsilon A_V + \epsilon^2 B_V$ and $\omega_2 = \frac{r}{3} + \epsilon^2 A_V + \epsilon B_V$, where

$$(8) \quad A_V = \sqrt[3]{\frac{r^3}{27} + \frac{rs}{6} + \frac{t}{2} + \sqrt{\Delta}}, \quad B_V = \sqrt[3]{\frac{r^3}{27} + \frac{rs}{6} + \frac{t}{2} - \sqrt{\Delta}},$$

with $\Delta = \Delta(r, s, t) = \frac{r^3 t}{27} - \frac{r^2 s^2}{108} + \frac{rst}{6} - \frac{s^3}{27} + \frac{t^2}{4}$ and $\epsilon = -\frac{1}{2} + \frac{i\sqrt{3}}{2}$ (see [1]).

In this paper, $\Delta(r, s, t) > 0$, then the cubic equation $x^3 - rx^2 - sx - t = 0$ has one real and two nonreal solutions, the latter being conjugate complex. Thus, the Binet formula for the generalized Tribonacci numbers can be expressed as:

$$(9) \quad V_n = \frac{P\alpha^n}{(\alpha - \omega_1)(\alpha - \omega_2)} - \frac{Q\omega_1^n}{(\alpha - \omega_1)(\omega_1 - \omega_2)} + \frac{R\omega_2^n}{(\alpha - \omega_2)(\omega_1 - \omega_2)},$$

where $P = V_2 - (\omega_1 + \omega_2)V_1 + \omega_1\omega_2V_0$, $Q = V_2 - (\alpha + \omega_2)V_1 + \alpha\omega_2V_0$ and $R = V_2 - (\alpha + \omega_1)V_1 + \alpha\omega_1V_0$.

In fact, the generalized Tribonacci sequence is the generalization of the well-known sequences like Tribonacci, Padovan, Narayana and third-order Jacobsthal. For example, $\{V_n(0, 0, 1; 1, 1, 1)\}_{n \geq 0}$, $\{V_n(0, 1, 0; 0, 1, 1)\}_{n \geq 0}$, are Tribonacci and Padovan sequences, respectively. In particular, the Binet formula for the generalized Tribonacci sequence $\{U_n\}_{n \geq 0} = \{V_n(0, 0, 1; r, s, t)\}_{n \geq 0}$ is expressed as follows.

Lemma 1. *The Binet formula for the generalized Tribonacci sequence $\{U_n\}_{n \geq 0}$ is*

$$(10) \quad U_n = \frac{\alpha^n}{(\alpha - \omega_1)(\alpha - \omega_2)} - \frac{\omega_1^n}{(\alpha - \omega_1)(\omega_1 - \omega_2)} + \frac{\omega_2^n}{(\alpha - \omega_2)(\omega_1 - \omega_2)},$$

where α , ω_1 and ω_2 are the roots of the cubic equation $x^3 - rx^2 - sx - t = 0$.

Proof. The validity of this formula can be confirmed using the recurrence relation. ■

In [10], using an inductive argument, authors give the matrix form of the n -th power of a companion matrix $M = \begin{bmatrix} r & s & t \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$ of $\{V_n\}_{n \geq 0}$

$$(11) \quad \begin{bmatrix} V_{n+2} \\ V_{n+1} \\ V_n \end{bmatrix} = \begin{bmatrix} r & s & t \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}^n \begin{bmatrix} V_2 \\ V_1 \\ V_0 \end{bmatrix}$$

and

$$(12) \quad \begin{bmatrix} r & s & t \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}^n = \begin{bmatrix} U_{n+2} & sU_{n+1} + tU_n & tU_{n+1} \\ U_{n+1} & sU_n + tU_{n-1} & tU_n \\ U_n & sU_{n-1} + tU_{n-2} & tU_{n-1} \end{bmatrix} \quad (n \geq 2),$$

where U_n is defined by equation (10).

And then give the Cassini-type identity for $\{U_n\}$ by taking the determinant of both sides of the matrix form equation (12)

$$(13) \quad U_n^3 + U_{n-1}^2 U_{n+2} + U_{n-2} U_{n+1}^2 - 2U_{n-1} U_n U_{n+1} - U_{n-2} U_n U_{n+2} = t^{n-2},$$

for $n \geq 2$.

More generally,

$$(14) \quad \begin{bmatrix} V_{n+4} & V_{n+3} + V_{n+2} & V_{n+3} \\ V_{n+3} & V_{n+2} + V_{n+1} & V_{n+2} \\ V_{n+2} & V_{n+1} + V_n & V_{n+1} \end{bmatrix} = M^n \begin{bmatrix} V_4 & V_3 + V_2 & V_3 \\ V_3 & V_2 + V_1 & V_2 \\ V_2 & V_1 + V_0 & V_1 \end{bmatrix},$$

for $n \geq 0$. Or equivalently, we can write the Cassini-type identity for $\{V_n\}$ by taking the determinant of both sides of the matrix form equation (14)

$$(15) \quad V_{n+2}^3 + V_{n+1}^2 V_{n+4} + V_n V_{n+3}^2 - V_{n+2}(2V_{n+1} V_{n+3} + V_n V_{n+4}) = t^n g_V(0),$$

where $g_V(0) = V_2^3 + V_1^2 V_4 + V_0 V_3^2 - V_2(2V_1 V_3 + V_0 V_4)$.

Now, we give the quadratic approximation of $\{V_n\}$ and then use this result to obtain the matrix form equation (14).

Theorem 2. *Let $\{V_n\}_{n \geq 0}$, α , ω_1 and ω_2 be as above. Then, we have for all integer $n \geq 0$*

(16)

$$\text{Quadratic app. of } \{V_n\} : \begin{cases} P\alpha^{n+2} = \alpha^2 V_{n+2} + \alpha(sV_{n+1} + tV_n) + tV_{n+1}, \\ Q\omega_1^{n+2} = \omega_1^2 V_{n+2} + \omega_1(sV_{n+1} + tV_n) + tV_{n+1}, \\ R\omega_2^{n+2} = \omega_2^2 V_{n+2} + \omega_2(sV_{n+1} + tV_n) + tV_{n+1}, \end{cases}$$

where $P = V_2 - (\omega_1 + \omega_2)V_1 + \omega_1\omega_2V_0$, $Q = V_2 - (\alpha + \omega_2)V_1 + \alpha\omega_2V_0$ and $R = V_2 - (\alpha + \omega_1)V_1 + \alpha\omega_1V_0$.

Proof. Using the Binet’s formula equation (9), we have

$$\begin{aligned} & \alpha V_{n+2} + (s + \omega_1\omega_2)V_{n+1} + tV_n \\ &= \frac{P\alpha^n(\alpha^3 + (s + \omega_1\omega_2)\alpha + t)}{(\alpha - \omega_1)(\alpha - \omega_2)} - \frac{Q\omega_1^n(\alpha\omega_1^2 + (s + \omega_1\omega_2)\omega_1 + t)}{(\alpha - \omega_1)(\omega_1 - \omega_2)} \\ &+ \frac{R\omega_2^n(\alpha\omega_2^2 + (s + \omega_1\omega_2)\omega_2 + t)}{(\alpha - \omega_2)(\omega_1 - \omega_2)} = (V_2 - (\omega_1 + \omega_2)V_1 + \omega_1\omega_2V_0)\alpha^{n+1}, \end{aligned}$$

the latter given that $\alpha\omega_1^2 + (s + \omega_1\omega_2)\omega_1 + t = 0$ and $\alpha\omega_2^2 + (s + \omega_1\omega_2)\omega_2 + t = 0$. Then, we get

$$(17) \quad \alpha V_{n+2} + (s + \omega_1\omega_2)V_{n+1} + tV_n = (V_2 - (\omega_1 + \omega_2)V_1 + \omega_1\omega_2V_0)\alpha^{n+1}.$$

Multiplying equation (17) by α and using $\alpha\omega_1\omega_2 = t$, we have

$$\begin{aligned} P\alpha^{n+2} &= \alpha^2 V_{n+2} + \alpha(s + \omega_1\omega_2)V_{n+1} + \alpha t V_n \\ &= \alpha^2 V_{n+2} + \alpha(sV_{n+1} + tV_n) + tV_{n+1}, \end{aligned}$$

where $P = V_2 - (\omega_1 + \omega_2)V_1 + \omega_1\omega_2V_0$. If we change α , ω_1 and ω_2 role above process, we obtain the desired result equation (16). ■

Now, we can re-prove equations equation (14) and equation (15) by using the above quadratic approximation of $\{V_n\}$ in equation (16).

Corollary 3. Let $M = \begin{bmatrix} r & s & t \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$ be a companion matrix of $\{V_n\}$. Then the matrix form of the n -th power M^n is given by equation (14) and the Cassini-type formula for $\{V_n\}$ is given by equation (15).

Proof. In equation (16), if we change α , ω_1 and ω_2 into the matrix M and change tV_{n+1} into the matrix $tV_{n+1}I_3$, then we have

$$(18) \quad M^n(V_2M^2 + (sV_1 + tV_0)M + tV_1I_3) = V_{n+2}M^2 + (sV_{n+1} + tV_n)M + tV_{n+1}I_3.$$

In fact, equation (18) holds for the following reason: Since

$$M \begin{bmatrix} V_{n+1} \\ V_n \\ V_{n-1} \end{bmatrix} = \begin{bmatrix} V_{n+2} \\ V_{n+1} \\ V_n \end{bmatrix} \quad \text{and} \quad M^n \begin{bmatrix} V_2 \\ V_1 \\ V_0 \end{bmatrix} = \begin{bmatrix} V_{n+2} \\ V_{n+1} \\ V_n \end{bmatrix},$$

we have

$$\begin{aligned} & M^n(V_2M^2 + (sV_1 + tV_0)M + tV_1I_3) \begin{bmatrix} V_2 \\ V_1 \\ V_0 \end{bmatrix} \\ &= V_2M^{n+2} \begin{bmatrix} V_2 \\ V_1 \\ V_0 \end{bmatrix} + (sV_1 + tV_0)M^{n+1} \begin{bmatrix} V_2 \\ V_1 \\ V_0 \end{bmatrix} + tV_1M^n \begin{bmatrix} V_2 \\ V_1 \\ V_0 \end{bmatrix} \\ &= V_2 \begin{bmatrix} V_{n+4} \\ V_{n+3} \\ V_{n+2} \end{bmatrix} + (sV_1 + tV_0) \begin{bmatrix} V_{n+3} \\ V_{n+2} \\ V_{n+1} \end{bmatrix} + tV_1 \begin{bmatrix} V_{n+2} \\ V_{n+1} \\ V_n \end{bmatrix} \\ &= \begin{bmatrix} V_2V_{n+4} + (sV_1 + tV_0)V_{n+3} + tV_1V_{n+2} \\ V_2V_{n+3} + (sV_1 + tV_0)V_{n+2} + tV_1V_{n+1} \\ V_2V_{n+2} + (sV_1 + tV_0)V_{n+1} + tV_1V_n \end{bmatrix}. \end{aligned}$$

Using $V_{n+3} = rV_{n+2} + sV_{n+1} + tV_n$ and $V_{n+4} = (r^2 + s)V_{n+2} + (rs + t)V_{n+1} + rtV_n$,

we have

$$\begin{aligned}
 M^n(V_2M^2 + (sV_1 + tV_0)M + tV_1I_3) & \begin{bmatrix} V_2 \\ V_1 \\ V_0 \end{bmatrix} \\
 &= \begin{bmatrix} V_4V_{n+2} + (sV_{n+1} + tV_n)V_3 + tV_{n+1}V_2 \\ V_3V_{n+2} + (sV_{n+1} + tV_n)V_2 + tV_{n+1}V_1 \\ V_2V_{n+2} + (sV_{n+1} + tV_n)V_1 + tV_{n+1}V_0 \end{bmatrix} \\
 &= (V_{n+2}M^2 + (sV_{n+1} + tV_n)M + tV_{n+1}I_3) \begin{bmatrix} V_2 \\ V_1 \\ V_0 \end{bmatrix}.
 \end{aligned}$$

Thus from equation (18) we have

$$\begin{aligned}
 M^n(V_2M^2 + (sV_1+tV_0)M + tV_1I_3) &= M^n \begin{bmatrix} V_4 & sV_3 + tV_2 & tV_3 \\ V_3 & sV_2 + tV_1 & tV_2 \\ V_2 & sV_1 + tV_0 & tV_1 \end{bmatrix} \\
 &= M^n \begin{bmatrix} V_4 & V_3 + V_2 & V_3 \\ V_3 & V_2 + V_1 & V_2 \\ V_2 & V_1 + V_0 & V_1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & t & 0 \\ 0 & s - t & t \end{bmatrix}
 \end{aligned}$$

and

$$\begin{aligned}
 V_{n+2}M^2 + (sV_{n+1} + tV_n)M + tV_{n+1}I_3 & \\
 &= \begin{bmatrix} V_{n+4} & sV_{n+3} + tV_{n+2} & tV_{n+3} \\ V_{n+3} & sV_{n+2} + tV_{n+1} & tV_{n+2} \\ V_{n+2} & sV_{n+1} + tV_n & tV_{n+1} \end{bmatrix} \\
 &= \begin{bmatrix} V_{n+4} & V_{n+3} + V_{n+2} & V_{n+3} \\ V_{n+3} & V_{n+2} + V_{n+1} & V_{n+2} \\ V_{n+2} & V_{n+1} + V_n & V_{n+1} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & t & 0 \\ 0 & s - t & t \end{bmatrix}.
 \end{aligned}$$

Since the matrix $\begin{bmatrix} 1 & 0 & 0 \\ 0 & t & 0 \\ 0 & s - t & t \end{bmatrix}$ is invertible, we obtain the desired result equation (14) and by taking the determinant of both sides of the matrix form equation (14) we obtain the desired result equation (15). The proof is completed. ■

Remark 4. For some positive integer k , if $r = k$, $s = 0$ and $t = 1$, then $\{U_n\}$ is the k -Narayana sequence $\{b_{k,n}\}$ investigated by Ramírez and Sirvent in [9]. The k -Narayana numbers can be expressed using Binet’s formula

$$\begin{aligned}
 (19) \quad b_{k,n} &= \frac{\alpha_k^n}{(\alpha_k - \omega_{k,1})(\alpha_k - \omega_{k,2})} - \frac{\omega_{k,1}^n}{(\alpha_k - \omega_{k,1})(\omega_{k,1} - \omega_{k,2})} \\
 &+ \frac{\omega_{k,2}^n}{(\alpha_k - \omega_{k,2})(\omega_{k,1} - \omega_{k,2})}.
 \end{aligned}$$

where $\alpha_k, \omega_{k,1}$ and $\omega_{k,2}$ are the roots of the cubic equation $x^3 - kx^2 - 1 = 0$. Furthermore, using the notation of equation (8), the roots given in [9] can be written as $\alpha_k = \frac{k}{3} + A_k + B_k, \omega_{k,1} = \frac{k}{3} + \epsilon A_k + \epsilon^2 B_k$ and $\omega_{k,2} = \frac{k}{3} + \epsilon^2 A_k + \epsilon B_k$, where

$$A_k = \sqrt[3]{\frac{k^3}{27} + \frac{1}{2} + \sqrt{\frac{k^3}{27} + \frac{1}{4}}}, B_k = \sqrt[3]{\frac{k^3}{27} + \frac{1}{2} - \sqrt{\frac{k^3}{27} + \frac{1}{4}}},$$

and $\epsilon = -\frac{1}{2} + \frac{i\sqrt{3}}{2}$ is a cubic root of unity.

From the Binet's formula equation (19), using the identities $\alpha_k + \omega_{k,1} + \omega_{k,2} = k, \alpha_k \omega_{k,1} + \alpha_k \omega_{k,2} + \omega_{k,1} \omega_{k,2} = 0$, we have for any integer $n \geq 2$:

$$\begin{aligned} & \alpha_k b_{k,n+2} + (\omega_{k,1} \omega_{k,2}) b_{k,n+1} + b_{k,n} \\ &= \frac{\alpha_k^n (\alpha_k^3 + (\omega_{k,1} \omega_{k,2}) \alpha_k + 1)}{(\alpha_k - \omega_{k,1})(\alpha_k - \omega_{k,2})} - \frac{\omega_{k,1}^n (\alpha_k \omega_{k,1}^2 + (\omega_{k,1} \omega_{k,2}) \omega_{k,1} + 1)}{(\alpha_k - \omega_{k,1})(\omega_{k,1} - \omega_{k,2})} \\ &+ \frac{\omega_{k,2}^n (\alpha_k \omega_{k,2}^2 + (\omega_{k,1} \omega_{k,2}) \omega_{k,2} + 1)}{(\alpha_k - \omega_{k,2})(\omega_{k,1} - \omega_{k,2})} = \alpha_k^{n+1}, \end{aligned}$$

the latter given that $\alpha_k \omega_{k,1}^2 + (\omega_{k,1} \omega_{k,2}) \omega_{k,1} + 1 = 0$ and $\alpha_k \omega_{k,2}^2 + (\omega_{k,1} \omega_{k,2}) \omega_{k,2} + 1 = 0$. Then, we get

$$(20) \quad \alpha_k b_{k,n+2} + (\omega_{k,1} \omega_{k,2}) b_{k,n+1} + b_{k,n} = \alpha_k^{n+1}.$$

Multiplying equation (20) by α_k , using $\alpha_k \omega_{k,1} \omega_{k,2} = 1$, and if we change $\alpha_k, \omega_{k,1}$ and $\omega_{k,2}$ in the role above process, we obtain the quadratic approximation of $\{b_{k,n}\}_{n \geq 0}$

$$(21) \quad \text{Quadratic app. of } \{b_{k,n}\} : \begin{cases} \alpha_k^n = b_{k,n} \alpha_k^2 + b_{k,n-2} \alpha_k + b_{k,n-1}, \\ \omega_{k,1}^n = b_{k,n} \omega_{k,1}^2 + b_{k,n-2} \omega_{k,1} + b_{k,n-1}, \\ \omega_{k,2}^n = b_{k,n} \omega_{k,2}^2 + b_{k,n-2} \omega_{k,2} + b_{k,n-1}, \end{cases}$$

where $\alpha_k, \omega_{k,1}$ and $\omega_{k,2}$ are the roots of the cubic equation $x^3 - x^2 - x - 1 = 0$.

In equation (20), if we replace α_k with the companion matrix Q_k and change T_{n-1} into the matrix $T_{n-1} I_3$, where I_3 is the 3×3 identity matrix, then we obtain the matrix form of Q_k^n :

$$Q_k^n = b_{k,n} Q_k^2 + b_{k,n-2} Q_k + b_{k,n-1} I_3 \left(= \begin{bmatrix} b_{k,n+2} & b_{k,n} & b_{k,n+1} \\ b_{k,n+1} & b_{k,n-1} & b_{k,n} \\ b_{k,n} & b_{k,n-2} & b_{k,n-1} \end{bmatrix} \right),$$

where $Q_k = \begin{bmatrix} k & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$.

The next corollary gives an alternative proof of the Binet’s formula for the generalized Tribonacci quaternions (see [1, Theorem 2.1]).

Corollary 5. For any integer $n \geq 0$, the n -th generalized Tribonacci quaternion is

$$(22) \quad Q_{V,n} = \frac{P\underline{\alpha}^n}{(\alpha - \omega_1)(\alpha - \omega_2)} - \frac{Q\underline{\omega}_1\omega_1^n}{(\alpha - \omega_1)(\omega_1 - \omega_2)} + \frac{R\underline{\omega}_2\omega_2^n}{(\alpha - \omega_2)(\omega_1 - \omega_2)},$$

where P, Q and R as in equation (9), $\underline{\alpha} = 1 + \alpha\mathbf{i} + \alpha^2\mathbf{j} + \alpha^3\mathbf{k}$, $\underline{\omega}_1 = 1 + \omega_1\mathbf{i} + \omega_1^2\mathbf{j} + \mathbf{k}$ and $\underline{\omega}_2 = 1 + \omega_2\mathbf{i} + \omega_2^2\mathbf{j} + \mathbf{k}$. If $V_0 = V_1 = 0$ and $V_2 = 1$, we get the classic Tribonacci quaternion.

Proof. For the equation (16), we have

$$\begin{aligned} & \alpha^2 Q_{V,n+2} + \alpha (sQ_{V,n+1} + tQ_{V,n}) + tQ_{V,n+1} \\ &= \alpha^2 (V_{n+2} + V_{n+3}\mathbf{i} + V_{n+4}\mathbf{j} + V_{n+5}\mathbf{k}) \\ &+ \alpha (sV_{n+1} + tV_n + (sV_{n+2} + tV_{n+1})\mathbf{i} + (sV_{n+3} + tV_{n+2})\mathbf{j} + (sV_{n+4} + tV_{n+3})\mathbf{k}) \\ &+ t (V_{n+1} + V_{n+2}\mathbf{i} + V_{n+3}\mathbf{j} + V_{n+4}\mathbf{k}) \\ &= \alpha^2 V_{n+2} + \alpha (sV_{n+1} + tV_n) + tV_{n+1} + (\alpha^2 V_{n+3} + \alpha (sV_{n+2} + tV_{n+1}) + tV_{n+2}) \mathbf{i} \\ &+ (\alpha^2 V_{n+4} + \alpha (sV_{n+3} + tV_{n+2}) + tV_{n+3}) \mathbf{j} \\ &+ (\alpha^2 V_{n+5} + \alpha (sV_{n+4} + tV_{n+3}) + tV_{n+4}) \mathbf{k}. \end{aligned}$$

From the identity $P\underline{\alpha}^{n+2} = \alpha^2 V_{n+2} + \alpha (sV_{n+1} + tV_n) + tV_{n+1}$ in Theorem 2, we obtain

$$(23) \quad \alpha^2 Q_{V,n+2} + \alpha (sQ_{V,n+1} + tQ_{V,n}) + tQ_{V,n+1} = P\underline{\alpha}^{n+2}.$$

Similarly, we have

$$(24) \quad \omega_1^2 Q_{V,n+2} + \omega_1 (sQ_{V,n+1} + tQ_{V,n}) + tQ_{V,n+1} = Q\underline{\omega}_1\omega_1^{n+2},$$

$$(25) \quad \omega_2^2 Q_{V,n+2} + \omega_2 (sQ_{V,n+1} + tQ_{V,n}) + tQ_{V,n+1} = R\underline{\omega}_2\omega_2^{n+2}.$$

Subtracting equation (24) from equation (23) gives

$$(26) \quad (\alpha + \omega_1)Q_{V,n+2} + (sQ_{V,n+1} + tQ_{V,n}) = \frac{P\underline{\alpha}^{n+2} - Q\underline{\omega}_1\omega_1^{n+2}}{\alpha - \omega_1}.$$

Similarly, subtracting equation (25) from equation (23) gives

$$(27) \quad (\alpha + \omega_2)Q_{V,n+2} + (sQ_{V,n+1} + tQ_{V,n}) = \frac{P\underline{\alpha}^{n+2} - R\underline{\omega}_2\omega_2^{n+2}}{\alpha - \omega_2}.$$

Finally, subtracting equation (27) from equation (26), we obtain

$$\begin{aligned} Q_{V,n+2} &= \frac{1}{\omega_1 - \omega_2} \left(\frac{P\underline{\alpha}\alpha^{n+2} - Q\underline{\omega_1}\omega_1^{n+2}}{\alpha - \omega_1} - \frac{P\underline{\alpha}\alpha^{n+2} - R\underline{\omega_2}\omega_2^{n+2}}{\alpha - \omega_2} \right) \\ &= \frac{P\underline{\alpha}\alpha^{n+2}}{(\alpha - \omega_1)(\alpha - \omega_2)} - \frac{Q\underline{\omega_1}\omega_1^{n+2}}{(\alpha - \omega_1)(\omega_1 - \omega_2)} + \frac{R\underline{\omega_2}\omega_2^{n+2}}{(\alpha - \omega_2)(\omega_1 - \omega_2)}. \end{aligned}$$

So, the corollary is proved. ■

3. CONCLUSIONS

Sequences of integer numbers have been studied over several years, with emphasis on studies of the well known Fibonacci sequence (and then the Lucas sequence) that is related to the golden ratio. In this paper, we also contribute for the study of Tribonacci sequence giving some identities which some of them involve generalized Tribonacci numbers. In the future, we intend to discuss the invertibility of these type matrices associated with these sequence (or quadratic approximation of generalized Tribonacci numbers with negative subscripts) using the identities given by Kuhapatanakul and Sukruan in [7].

Acknowledgement

The author would like to thank the referees for their comments that helped me to improve this article.

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Received 25 June 2018

Revised 23 July 2018

Accepted 3 September 2018