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On Alexander-Conway polynomials of two-bridge links

Pierre-Vincent Koseleff, Daniel Pecker

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Abstract

We consider Conway polynomials of two-bridge links as Euler continuant polynomials. As a consequence, we obtain new and elementary proofs of classical Murasugi's 1958 alternating theorem and Hartley's 1979 trapezoidal theorem. We give a modulo 2 congruence for links, which implies the classical Murasugi's 1971 congruence for knots. We also give sharp bounds for the coefficients of Euler continuants and deduce bounds for the Alexander polynomials of two-bridge links. These bounds improve and generalize those of Nakanishi-Suketa'96. We easily obtain some bounds for the roots of the Alexander polynomials of two-bridge links. This is a partial answer to Hoste's conjecture on the roots of Alexander polynomials of alternating knots.

MSC2010: 57M25, 11C08

Keywords: Euler continuant polynomial, two-bridge link, Conway polynomial, Alexander polynomial

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1 Introduction

In this paper, we consider the Conway polynomial of a two-bridge link as an Euler continuant polynomial. We study the problem of determining whether a given polynomial is the Conway polynomial of a two-bridge link (or knot), or equivalently, if it is a Euler continuant polynomial. For small degrees, this problem can be solved by an exhaustive search

of possible two-bridge links. Here, we give necessary conditions on the coefficients of the polynomial, which can be tested for high degree polynomials.

In section 2 we present Euler continuant polynomials and give some properties of their coefficients. We show their relations with the Fibonacci polynomials f_k defined by:

$$f_0 = 0, f_1 = 1, f_{n+2}(z) = zf_{n+1}(z) + f_n(z).$$

In section 3, we recall the definitions of two-bridge links and we present the description of the Conway polynomial of a two-bridge link as an extended Euler continuant polynomial. We obtain a characterization of modulo 2 two-bridged Conway polynomials.

Theorem 3.3. *Let $\nabla(z) \in \mathbf{Z}[z]$ be the Conway polynomial of a rational link (or knot). There exists a Fibonacci polynomial $f_D(z)$ such that $\nabla(z) \equiv f_D(z) \pmod 2$.*

We give a simple method (Algorithm 3.4) that determines the integer D such that $\nabla(z) \equiv f_D(z) \pmod 2$. This is used to test when $\nabla(z) \equiv 1 \pmod 2$, which is a necessary condition to be a two-bridge Lissajous knot.

These results are applied in section 4 to the Conway polynomials of two-bridge links denoted

$$\nabla_m(z) = \sum_{k=0}^{\lfloor \frac{m}{2} \rfloor} c_{m-2k} z^{m-2k}.$$

Theorem 4.1. *For $k \geq 0$,*

$$|c_{m-2k}| \leq \binom{m-k}{k} |c_m| .$$

If equality holds for some positive integer $k < \lfloor \frac{m}{2} \rfloor$, then it holds for all integers. In this case, the link is isotopic to a link of Conway form $C(2, -2, 2, \ldots, (-1)^{m+1}2)$ or $C(2, 2, \ldots, 2)$, up to mirror symmetry.

When $|c_m| \neq 1$, we have the following sharper bounds:

Theorem 4.4. *Let $g \geq 1$ be the greatest prime divisor of c_m, and $m \geq 2k \geq 2$. Then*

$$|c_{m-2k}| \leq \left(\binom{m-k-1}{k} + \frac{1}{g}\left(\binom{m-k-1}{k-1} - 1 \right) \right) |c_m| + 1.$$

Equality holds for links of Conway forms $C(2g, 2, 2, \ldots, 2)$ and $C(2g, -2, 2, \ldots, (-1)^{m+1}\, 2)$.

In section 5, we apply our results to the Alexander polynomials. Our modulo 2 congruence of Theorem 3.3 provides a simple proof of a congruence of Murasugi [21] for periodic knots (two-bridge knots have period two). Moreover, we deduce a congruence for the Hosokawa polynomials of two-bridge links (Corollary 5.5).

Then, we obtain a simple proof of both the Murasugi alternating theorem [22, 20], and the Hartley trapezoidal theorem [7] (see also [9]) using the trapezoidal property:

Theorem 4.6. *Let K be a two-bridge link (or knot). Let*

$$\nabla_K = c_m\Big(\sum_{i=0}^{\lfloor\frac{m}{2}\rfloor}(-1)^i\alpha_i f_{m-2i+1}\Big), \quad \alpha_0 = 1$$

be its Conway polynomial written in the Fibonacci basis. Then we have

1. $\alpha_j \geq 0,\ j = 0, \ldots, \lfloor\frac{m}{2}\rfloor$.
2. *If $\alpha_i = 0$ for some $i > 0$ then $\alpha_j = 0$ for $j \geq i$.*

We conclude this section with bounds for the coefficients of the Alexander coefficients. These bounds improve those of Nakanishi and Suketa for the Alexander polynomials of two-bridge knots (see [23, theorems 2 and 3]). Moreover, they are sharp and hold for any k.

We prove that the conditions on Conway coefficients are sharper than the conditions on the Alexander coefficients deduced from them.

In section 6, we conclude our paper with the following convexity conjecture:

Conjecture 6.2. *Let $\Delta(t) = a_0 - a_1(t+t^{-1}) + a_2(t^2+t^{-2}) - \cdots + (-1)^n a_n(t^n+t^{-n})$ be the Alexander polynomial of a two-bridge knot. Then there exists an integer $k \leq n$ such that $(a_0, \ldots, a_k)$ is convex and $(a_k, \ldots, a_n)$ is concave.*

We have tested this conjecture for all two-bridge knots with 20 crossings or fewer.

We also deduce some bounds for the roots of Alexander polynomials of two-bridge links (or knots) from the properties of Euler continuant polynomials. This gives some partial answer to the Hoste conjecture 6.3.

2 Extended Euler continuant polynomial

We define the extended Euler continuant polynomial $D_m(b_1, \ldots, b_m)(z)$ as the determinant of the tridiagonal matrix

$$\begin{pmatrix} b_1 z & -1 & 0 & \ldots & 0 \\ 1 & b_2 z & -1 & \ddots & \vdots \\ 0 & & \ddots & \ddots & 0 \\ \vdots & \ddots & \ddots & & -1 \\ 0 & \ldots & 0 & 1 & b_m z \end{pmatrix}. \tag{1}$$

The polynomials D_i satisfy the recurrence relation

$$D_{-1} = 0,\ D_0 = 1,\ D_k = b_k z D_{k-1} + D_{k-2}. \tag{2}$$

When $z = 1$, this is the classical Euler continuant polynomial (see [14]).

When all the b_i are equal to 1, we obtain the Fibonacci polynomials defined by

$$f_0 = 0, f_1 = 1, f_{n+2}(z) = zf_{n+1}(z) + f_n(z),\ n \in \mathbf{Z}. \tag{3}$$

Let us recall some basic facts about Fibonacci polynomials.

Lemma 2.1. *For $m \geq 0$:*

$$f_{m+1}(z) = \sum_{k=0}^{\lfloor \frac{m}{2} \rfloor} \binom{m-k}{k} z^{m-2k}.$$

Proof. By induction on m. The result is clear for $m = 1$ and for $m = 2$. Let us suppose the result true for $m-1$ and m. By induction, the coefficient of z^{m-2k} is $\binom{m-1-k}{k}$ in $zf_m(z)$, and $\binom{m-1-k}{k-1}$ in $f_{m-1}(z)$. Consequently, the coefficient of z^{m-2k} in $f_{m+1}(z)$ is

$$\binom{m-1-k}{k} + \binom{m-1-k}{k-1} = \binom{m-k}{k}.$$

□

Remark 2.2. This means that the Fibonacci polynomials can be read on the diagonals of Pascal's triangle. When $z = 1$, we recover the classical Lucas identity

$$F_m = \sum_{k=0}^{\lfloor \frac{m}{2} \rfloor} \binom{m-k}{k},$$

where F_m are the Fibonacci numbers ($F_0 = 0,\ F_1 = 1, \ldots, F_{n+1} = F_n + F_{n-1}$).

We shall need the following explicit notation for Euler continuant polynomials:

$$D_m(z) = \sum_{k=0}^{\lfloor \frac{m}{2} \rfloor} c_{m-2k}(b_1, \ldots, b_m) z^{m-2k}. \tag{4}$$

We obtain some properties of $c_{m-2k}(b_1, \ldots, b_m)$, considered as a polynomial in the m variables $b_1, \ldots, b_m$.

Proposition 2.3. *Let $\mathcal{M}$ be the set of all monomials $\dfrac{b_1 \cdots b_m}{b_{i_1} b_{i_1+1} \cdots b_{i_k} b_{i_k+1}}$, where $k \neq 0$ and $i_h + 1 < i_{h+1}$. Let $\mathcal{M}_j$ be the subset of all monomials of $\mathcal{M}$ that are relatively prime to b_j. Then we have*

1. *The polynomial $c_{m-2k}(b_1, \ldots, b_m)$ is the sum of all monomials of $\mathcal{M}$.*
2. *The set $\mathcal{M}$ has $\binom{m-k}{k}$ elements.*
3. *The monomials of $\mathcal{M}$ do not have a common divisor except 1.*
4. *The number of elements of $\mathcal{M}_j$ is at least $\binom{m-1-k}{k-1}$.*
5. *If $m \geq 4$, then the monomials of $\mathcal{M}_j$ do not have a common divisor except 1.*

Proof.

1. This is a classical property of the Euler continuant (see [14])
2. This number is $c_{m-2k}(1,1,\dots,1)$, which is a coefficient of the Fibonacci polynomial

$$f_{m+1}(z) = \sum_{k=0}^{\lfloor \frac{m}{2} \rfloor} c_{m-2k}(1,1,\dots,1) z^{m-2k} = \sum_{k=0}^{\lfloor \frac{m}{2} \rfloor} \binom{m-k}{k} z^{m-2k}.$$

3. For every integer $i \leq m$, there is an element of $\mathcal{M}$ which is not divisible by b_i. Hence the GCD of the elements of $\mathcal{M}$ is 1.
4. Let $1 \leq j \leq m$ and $\mathbf{b} = (1,\dots,1,0,1,\dots,1)$ where $b_j = 0$, and $b_k = 1$ for $k \neq j$. Let us define the polynomials g_n, for $n \leq m$ by $g_n(z) = D_n(\mathbf{b})(z)$. The number of elements of $\mathcal{M}_j$ is the coefficient $c_{m-2k}(\mathbf{b})$ of $g_m(z)$.

   If $j = 1$, then we have $g_1 = 0$, $g_2 = 1$. Then, an easy induction shows that $g_n = zg_{n-1} + g_{n-2}$ is the Fibonacci polynomial $g_n = f_{n-1}$.

   If $j > 1$, then we have

$$g_1 = f_2,\ \dots,\ g_{j-1} = f_j,\ g_j = f_{j-1}, \quad \text{and} \quad g_{n+1} = zg_n + g_{n-1} \quad \text{if} \quad n \geq j.$$

   Let us write $p(z) \succeq q(z)$ when each coefficient of p is greater than or equal to the corresponding coefficient of q. We have $f_{k+2} \succeq f_k$, and therefore $g_{j+1} = zf_{j-1} + f_j \succeq zf_{j-1} + f_{j-2} = f_j$. Then a simple induction shows that $g_m \succeq f_{m-1}$, and consequently $c_{m-2k}(\mathbf{b}) \geq \binom{m-1-k}{k-1}$.
5. Since $m \geq 4$, for every $i \neq j$, there is a monomial which is not divisible by b_i. Consequently, the GCD of the elements of $\mathcal{M}_j$ is 1. □

3 Conway polynomials of two-bridge links

A two-bridge knot (or link) admits a diagram in Conway's normal form. This form, denoted by $C(a_1, a_2, \dots, a_n)$ where a_i are integers, is explained by the following picture (see [4, 22]).

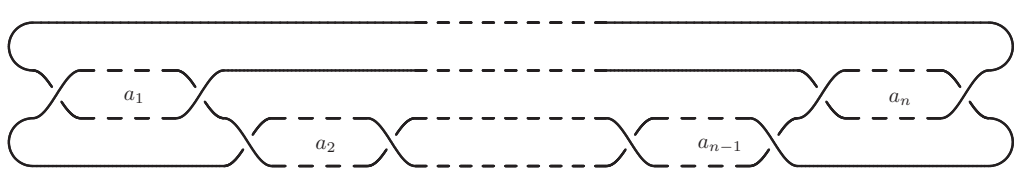

Figure 1: Conway's normal forms

The number of twists is denoted by the integer $|a_i|$, and the sign of a_i is defined as follows: if i is odd, then the right twist is positive, if i is even, then the right twist is negative. On Fig. 1 the a_i are positive (the a_1 first twists are right twists).

The two-bridge links are classified by their Schubert fractions (see [24])

$$\frac{\alpha}{\beta} = a_1 + \cfrac{1}{a_2 + \cfrac{1}{\cdots + \cfrac{1}{a_n}}} = [a_1, \ldots, a_n], \quad \alpha > 0.$$

We shall denote $S(\frac{\alpha}{\beta})$ a two-bridge link with Schubert fraction $\frac{\alpha}{\beta}$. The two-bridge links $S(\frac{\alpha}{\beta})$ and $S(\frac{\alpha'}{\beta'})$ are equivalent if and only if $\alpha = \alpha'$ and $\beta' \equiv \beta^{\pm 1} (\mathrm{mod}\ \alpha)$. The integer α is odd for a knot, and even for a two-component link.

When $\alpha\beta$ is even, one shows (see [13, p. 26], [15, 11]) that there is a unique continued fraction expansion $\frac{\alpha}{\beta} = [2b_1, 2b_2, \ldots, 2b_n],\ b_i \in \mathbf{Z} - \{0\}$. It means that any oriented two-bridge link can be put in the form shown in Figure 2. It will be denoted by $C(2b_1, 2b_2, \ldots, 2\,b_m)$, including the indicated orientation. This is a two-component link if and only if m is odd.

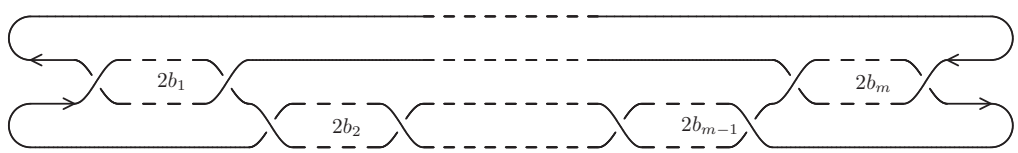

Figure 2: Oriented two-bridge links (m odd)

The Conway polynomial $\nabla_K(z) \in \mathbf{Z}[z]$ is a polynomial invariant of the oriented link K (see [5]). When K is a two-bridge link its Conway polynomial ∇_m is given by the following method (see [25] and [5, Th. 8.7.4]):

Theorem 3.1 ([25, 5]) *Let us consider the oriented two-bridge link*

$$C(2b_1, -2b_2, \ldots, (-1)^{m-1} 2b_m).$$

Its Conway polynomial $\nabla_m(z)$ is the Euler continuant polynomial $D_m(b_1, \ldots, b_m)(z)$.

Example 3.2 (The torus links) *The Conway polynomial of the torus link $\mathrm{T}(2, m)$ is the Fibonacci polynomial $f_m(z)$ (see [12, 17]).*

Consequently, the following result gives in fact a characterization of modulo 2 Conway polynomials of two-bridge links.

Theorem 3.3. *Let $\nabla(z) \in \mathbf{Z}[z]$ be the Conway polynomial of a rational link (or knot). There exists a Fibonacci polynomial $f_d(z)$ such that $\nabla(z) \equiv f_d(z) \,(\mathrm{mod}\, 2)$.*

Proof. Let us write $(a,b) \equiv (c,d) \pmod 2$ when $a \equiv c \pmod 2$ and $b \equiv d \pmod 2$. We will show by induction on m that there exist integers d and $e = \pm 1$ such that $(D_{m-1}, D_m) \equiv (f_{d-e}, f_d) \pmod 2$.

The result is true for $m = 0$ as $(\nabla_{-1}, \nabla_0) = (0,1) = (f_0, f_1)$, that is $d = e = 1$.

Suppose that $(\nabla_{m-1}, \nabla_m) \equiv (f_{d-e}, f_d) \pmod 2$, with $e = \pm 1$ for some $m \geq 0$. Then we have $\nabla_{m+1} = b_{m+1} z \nabla_m + \nabla_{m-1}$.

If $b_{m+1} \equiv 0 \pmod 2$ then $\nabla_{m+1} \equiv \nabla_{m-1} \equiv \nabla_{d-e} \pmod 2$ and $(\nabla_m, \nabla_{m+1}) \equiv (f_d, f_{d-e})$.

If $b_{m+1} \equiv 1 \pmod 2$ then $\nabla_{m+1} \equiv z f_d + f_{d-e} \equiv f_{d+e} \pmod 2$. Consequently $(\nabla_m, \nabla_{m+1}) \equiv (f_d, f_{d+e})$. □

We thus deduce a fast algorithm for the determination of the integer d such that $\nabla_m \equiv f_d \pmod 2$, see also [3].

Algorithm 3.4. Let us define the sequences of integers e_i and d_i, $i = 0, \ldots, m$, by

$$e_0 = 1,\ d_0 = 1,\ e_{i+1} = -(-1)^{b_{i+1}} e_i,\ d_{i+1} = d_i + e_{i+1}.$$

Then we have $\nabla_m(z) \equiv f_d(z) \pmod 2$ where $d = |d_m|$.

Remark 3.5. Let us consider the two-bridge link $K = C(2b_1, -2b_2, \ldots, (-1)^{m-1} 2b_m)$. From [27], the crossing number N of K is $2\sum_{i=1}^m |b_i| - \#\{i, b_i b_{i+1} < 0\} \geq m+1$. We deduce that one computes d such that $\nabla_K \equiv f_d \pmod 2$ in $\mathcal{O}(N)$ steps.

The torus knot $\mathrm{T}(2,m)$ is the two-bride knot $S(m)$ of crossing number m. The rational number $\frac{m}{m-1}$ has the continued fraction expansion of length $m-1$: $[2, -2, \ldots, (-1)^m 2]$. That shows that the inequality $m \leq N - 1$ is sharp.

Jones, Przytycki, and Lamm proved that the Conway polynomial of a two-bridge Lissajous knot satisfies the congruence $\nabla(z) \equiv 1 \pmod 2$, that is $d = 0$ (see [8, 18]). Using Algorithm 3.4 we deduce the number of two-bridge knots with a Conway polynomial congruent to 1 modulo 2 (see Table 1 and compare [2]).

Crossing Number	3	4	5	6	7	8	9	10	11	12
Two-bridge	1	1	2	3	7	12	24	45	91	176
$\nabla(t) \equiv 1$	0	0	1	1	2	4	8	13	26	51

Crossing Number	13	14	15	16	17	18	19	20	21	22
Two-bridge	352	693	1387	2752	5504	10965	21931	43776	87552	174933
$\nabla(t) \equiv 1$	97	185	365	705	1369	2675	5233	10211	20011	39221

Table 1: The number of two-bridge knots, and two-bridge knots with Conway polynomial congruent to 1 modulo 2.

4 Inequalities for Conway Polynomials

We shall write the Conway polynomial of a two-bridge link

$$\nabla_m(z) = \sum_{k=0}^{\lfloor \frac{m}{2} \rfloor} c_{m-2k} z^{m-2k}.$$

Theorem 4.1. *For $k \geq 0$,*

$$|c_{m-2k}| \leq \binom{m-k}{k} |c_m| .$$

If equality holds for some integer $k < \lfloor \frac{m}{2} \rfloor$, then it holds for all integers. In this case, the link is isotopic to the torus link $T(2,m)$ or to the link $C(2,2,\ldots,2)$, up to mirror symmetry.

Proof. By Proposition 2.3, the number of monomials of $c_{m-2k}(b_1,\ldots,b_m)$ is $\binom{m-k}{k}$. The result follows since no monomial is greater than $|c_m| = |b_1 \cdots b_m|$.

If equality holds for some positive integer $k < \lfloor \frac{m}{2} \rfloor$, then for all i, j, $b_i b_{i+1} = b_j b_{j+1} = \pm 1$, which implies the result. □

Example 4.2. The knot 10_{145} has Conway polynomial $P = 1 + 5z^2 + z^4$. We have $P \equiv f_5 \pmod 2$, but P does not satisfy the condition $|c_2| \leq 3$, and then 10_{145} is not a two-bridge knot.

The knot $11n109$ has Conway polynomial $1+6z^2+z^4-z^6$. It satisfies the bounds of Theorem 4.1: $|c_2| \leq 6$, $|c_4| \leq 5$, but not the equality condition: $c_2 = 6$ whereas $c_4 \neq 5$. Consequently, $11n109$ is not a two-bridge knot.

We shall use the following lemma, which generalizes the inequality $a + b \leq ab + 1$, valid for positive integers (see also [23]).

Lemma 4.3. *Let p_i, $i \in \mathcal{S}$ be relatively prime divisors of $p = x_1 x_2 \cdots x_m$ in $\mathbf{Q}[x_1,\ldots,x_m]$. Let $\mathbf{b} = (b_1,\ldots,b_m)$ be a m-tuple of positive integers. Then*

$$\sum_{i \in \mathcal{S}} p_i(\mathbf{b}) \leq \Big(\mathrm{card}(\mathcal{S}) - 1\Big) p(\mathbf{b}) + 1. \tag{5}$$

Proof. We do not suppose the p_i distinct. Let us prove the result by induction on $k = \mathrm{card}(\mathcal{S})$. The result is clear if $k = 1$, we have $p_1 = \pm 1$, and the inequality is $\pm 1 \leq 1$.

If all the $p_i = 1$, the result is clear. Otherwise, let x_h be a divisor of some p_i.

Let $\mathcal{S}_1 = \{i \in \mathcal{S} : \ x_h | p_i\}$, and $\mathcal{S}_2 = \mathcal{S} - \mathcal{S}_1$. We have $k = k_1 + k_2$, where $k_j = \mathrm{card}(\mathcal{S}_j)$. Let $q_j = \mathrm{GCD}\{p_i, i \in \mathcal{S}_j\}$, then q_1 and q_2 are coprime, and $q_1 q_2$ is a divisor of p.

By induction we obtain for $j = 1, 2$:

$$\sum_{i\in\mathcal{S}_j} p_i(\mathbf{b}) \le q_j(\mathbf{b})\Big((k_j-1)\frac{p(\mathbf{b})}{q_j(\mathbf{b})}+1\Big) = (k_j-1)p(\mathbf{b}) + q_j(\mathbf{b}).$$

Adding these two inequalities we get

$$\begin{aligned}\sum_{i\in\mathcal{S}} p_i(\mathbf{b}) &\le (k_1+k_2-1)p(\mathbf{b}) + q_1(\mathbf{b}) + q_2(\mathbf{b}) - p(\mathbf{b})\\ &\le (k_1+k_2-1)p(\mathbf{b}) + q_1(\mathbf{b})q_2(\mathbf{b}) - p(\mathbf{b}) + 1,\end{aligned}$$

which proves the result, since $q_1(\mathbf{b})q_2(\mathbf{b}) \le p(\mathbf{b})$. □

With this lemma we can prove:

Theorem 4.4. *Let $g \ge 1$ be the greatest prime divisor of c_m, and let $k \ne 0$. Then*

$$|c_{m-2k}| \le \Big(\tbinom{m-k-1}{k} + \tfrac{1}{g}\big(\tbinom{m-k-1}{k-1}-1\big)\Big)\,|c_m| + 1.$$

Equality holds for $(b_1,\dots,b_m) = (g,1,\dots,1)$ and $(b_1,\dots,b_m) = (g,-1,\dots,(-1)^m)$.

Proof. If $k = 1$, there are $m-1$ monomials in the polynomial $c_{m-2}(b_1,\dots,b_m)$, by Proposition 2.3. Then, using Lemma 4.3 and the notation $|\mathbf{b}| = (|b_1|,\dots,|b_m|)$, we get

$$|c_{m-2}| = |c_{m-2}(\mathbf{b})| \le c_{m-2}(|\mathbf{b}|) \le (m-2)c_m(|\mathbf{b}|) + 1 = (m-2)\,|c_m| + 1.$$

Now, suppose $k \ge 2$. Let g be the greatest prime divisor of the integer $c_m = b_1\cdots b_m$, and suppose that $g \mid b_j$. Let N be the number of monomials of $c_{m-2k}(b_1,\dots,b_m)$ that are prime to the monomial b_j. By Proposition 2.3, these monomials are relatively prime, and $N \ge \binom{m-1-k}{k-1}$. Using Lemma 4.3 we obtain: $\sum_{p_i\in\mathcal{M}_j} p_i(\mathbf{b}) \le (N-1)\dfrac{|c_m|}{|b_j|} + 1$ and then

$$\begin{aligned}|c_{m-2k}| = \Big|\textstyle\sum_{p_i\in\mathcal{M}} p_i(\mathbf{b})\Big| &\le \Big(\frac{N-1}{g} + \big(\tbinom{m-k}{k} - N\big)\Big)\,|c_m| + 1\\ &= \Big(\tbinom{m-k}{k} - N(1-\tfrac{1}{g}) - \tfrac{1}{g}\Big)\,|c_m| + 1\\ &\le \Big(\tbinom{m-k}{k} - \tbinom{m-1-k}{k-1}(1-\tfrac{1}{g}) - \tfrac{1}{g}\Big)\,|c_m| + 1\\ &= \Big(\tbinom{m-1-k}{k} + \tfrac{1}{g}\big(\tbinom{m-1-k}{k-1}-1\big)\Big)\,|c_m| + 1.\end{aligned}$$

For $\mathbf{b} = (g,1,\dots,1)$ we obtain $N = \binom{m-1-k}{k-1}$, $c_m = g$, and $c_{m-2k} = g\binom{m-1-k}{k} + \binom{m-1-k}{k-1}$, and equality holds throughout.

For $\mathbf{b} = (g,-1,1,\dots,(-1)^m)$ we get $c_{m-2k} = (-1)^{\lfloor\frac{m}{2}\rfloor+k}\Big(g\binom{m-1-k}{k} + \binom{m-1-k}{k-1}\Big)$. □

Example 4.5. The knot $13n3010$ has Conway polynomial $\nabla = 1 + 10\,z^2 + 4\,z^4 - 2\,z^6$. It satisfies all conditions of Theorems 4.1 and 3.3 but not those of Theorem 4.4.

Now, we will express the Conway polynomials in terms of Fibonacci polynomials, and show that their coefficients are alternating.

Theorem 4.6. *Let K be a two-bridge link (or knot). Let*

$$\nabla_K = c_m\Big(\sum_{i=0}^{\lfloor\frac{m}{2}\rfloor}(-1)^i\alpha_i f_{m-2i+1}\Big), \quad \alpha_0 = 1$$

be its Conway polynomial expressed in the Fibonacci basis. Then we have

1. $\alpha_j \geq 0,\ j = 0, \ldots, \lfloor\frac{m}{2}\rfloor$.
2. *If $\alpha_i = 0$ for some $i > 0$ then $\alpha_j = 0$ for $j \geq i$.*

Proof. We have $\nabla_0 = f_1$, $\nabla_1 = b_1 f_2$, $\nabla_2 = b_1 b_2\Big(f_3 - (1 - \frac{1}{b_1 b_2})f_1\Big)$.

Let us show by induction that if

$$\nabla_m = b_1 \cdots b_m\Big(\sum_{i=0}^{\lfloor\frac{m}{2}\rfloor}(-1)^i\alpha_i f_{m+1-2i}\Big),\ \nabla_{m-1} = b_1 \cdots b_{m-1}\Big(\sum_{i=0}^{\lfloor\frac{m-1}{2}\rfloor}(-1)^i\beta_i f_{m-2i}\Big)$$

then $\alpha_j \geq \beta_j \geq 0$, and if $\alpha_i = 0$ for some i, then $\alpha_j = 0$ for $j \geq i$.

The result is true for $m = 2$ from the expressions of ∇_1 and ∇_2. Using $zf_{m+1-2i} = f_{m+2-2i} - f_{m-2i}$ and $\nabla_{m+1} = b_{m+1}z\nabla_m + \nabla_{m-1}$, we deduce that

$$\nabla_{m+1} = b_1 \cdots b_{m+1}\Big(\sum_{i=0}^{\lfloor\frac{m+1}{2}\rfloor}(-1)^i\gamma_i f_{m+2-2i}\Big),$$

where $\gamma_0 = 1$ and

$$\gamma_i = \alpha_i + (\alpha_{i-1} - \beta_{i-1}) + (1 - \tfrac{1}{b_m b_{m+1}})\beta_{i-1},\ i = 1, \ldots, \lfloor\tfrac{m+1}{2}\rfloor. \tag{6}$$

As $|b_m b_{m+1}| \geq 1$, we deduce by induction that $\gamma_i \geq \alpha_i \geq 0$.

Furthermore, if $\gamma_i = 0$, then by Formula (6) $\alpha_i = 0$, and then, by induction, $\alpha_j = \beta_j = 0$ for $j \geq i$. Finally, by Formula (6), we get $\gamma_j = 0$ for $j \geq i$. □

5 Applications to the Alexander polynomial

In this section, we will see that our necessary conditions on the Euler continuant polynomials imply analogous necessary conditions on both Conway coefficients and Alexander coefficients of two-bridge knots and links. These conditions are improvements of the classical results.

The Conway and the Alexander polynomials of a knot K will be denoted by

$$\nabla_K(z) = 1 + \tilde{c}_1 z^2 + \cdots + \tilde{c}_n z^{2n}$$

and

$$\Delta_K(t) = a_0 - a_1(t + t^{-1}) + \cdots + (-1)^n a_n(t^n + t^{-n}).$$

The Alexander polynomial $\Delta_K(t)$ is deduced from the Conway polynomial:

$$\Delta_K(t) = \nabla_K\Big(t^{1/2} - t^{-1/2}\Big).$$

It is often normalized so that a_n is positive. Thanks to this formula, it is not difficult to deduce the Alexander polynomial from the Conway polynomial. If we use the Fibonacci basis, it is even easier to deduce the Conway polynomial of a knot from its Alexander polynomial.

Lemma 5.1. *If* $z = t^{1/2} - t^{-1/2}$, *and* $n \in \mathbf{Z}$ *is an integer, then we have the identity*

$$f_{n+1}(z) + f_{n-1}(z) = (t^{1/2})^n + (-t^{-1/2})^n,$$

where $f_k(z)$ *are the Fibonacci polynomials.*

Proof. Let $A = \begin{bmatrix} z & 1 \\ 1 & 0 \end{bmatrix}$ be the (polynomial) Fibonacci matrix. If $z = t^{1/2} - t^{-1/2}$, the eigenvalues of A are $t^{1/2}$ and $-t^{-1/2}$, and consequently $\operatorname{tr} A^n = (t^{1/2})^n + (-t^{-1/2})^n$. On the other hand, we have $A^n = \begin{bmatrix} f_{n+1}(z) & f_n(z) \\ f_n(z) & f_{n-1}(z) \end{bmatrix}$, and then $\operatorname{tr} A^n = f_{n+1}(z) + f_{n-1}(z)$. □

From Lemma 5.1, we immediately deduce:

Proposition 5.2. *Let the Laurent polynomial* $P(t)$ *be defined by*

$$P(t) = a_0 - a_1(t + t^{-1}) + a_2(t^2 + t^{-2}) - \cdots + (-1)^n a_n(t^n + t^{-n}).$$

We have

$$P(t) = \sum_{k=0}^{n} (-1)^k (a_k - a_{k+1}) f_{2k+1}(z),$$

where $z = t^{1/2} - t^{-1/2}$, *and* $a_{n+1} = 0$.

We deduce a useful formula (by substituting $a_0 = \ldots = a_n = 1$).

$$f_{2n+1}\big(t^{1/2} - t^{-1/2}\big) = (t^n + t^{-n}) - (t^{n-1} + t^{1-n}) + \cdots + (-1)^n. \tag{7}$$

Then, we deduce a simple proof of an elegant criterion due to Murasugi ([21, 3])

Corollary 5.3 (Murasugi (1971)) *Let* $\Delta(t) = a_0 - a_1(t + t^{-1}) + a_2(t^2 + t^{-2}) - \cdots + (-1)^n a_n(t^n + t^{-n})$ *be the Alexander polynomial of a two-bridge knot. There exists an integer* $k \leq n$ *such that* $a_0, a_1, \ldots, a_k$ *are odd, and* $a_{k+1}, \ldots, a_n$ *are even.*

Proof. If K is a two-bridge knot, its Conway polynomial is a modulo 2 Fibonacci polynomial f_{2k+1} by theorem 3.3. By Proposition 5.2 we have $f_{2k+1}\big(t^{1/2}-t^{-1/2}\big) = (t^k+t^{-k}) - (t^{k-1}+t^{1-k}) + \cdots + (-1)^k$, and the result follows. □

Remark 5.4. This congruence may be used as a simple criterion to prove that some knots cannot be two-bridge knots. There is a more efficient criterion by Kanenobu [10, 26] using the Jones and Q polynomials.

We also deduce an analogous result for two-component links (see also [3, p. 186])

Corollary 5.5 (Modulo 2 Hosokawa polynomials of two-bridge links) *Let* $\Delta(t) = \big(t^{1/2}-t^{-1/2}\big)\Big(a_0 - a_1(t+t^{-1}) + a_2(t^2+t^{-2}) - \cdots + (-1)^n a_n(t^n+t^{-n})\Big)$ *be the Alexander polynomial of a two-component two-bridge link. Then all the coefficients* a_i *are even or there exists an integer* $k \leq n$ *such that* $a_k, a_{k-2}, a_{k-4}, \ldots$ *are odd, and the other coefficients are even.*

Proof. If K is a two-component two-bridge link, its Conway polynomial is an odd Fibonacci polynomial modulo 2, that is of the form $f_{2h}(z)$. An easy induction shows that

$$f_{4k}\big(t^{1/2}-t^{-1/2}\big) = \big(t^{1/2}-t^{-1/2}\big)\big(u_1+u_3+\cdots+u_{2k-1}\big)$$

and

$$f_{4k+2}\big(t^{1/2}-t^{-1/2}\big) = \big(t^{1/2}-t^{-1/2}\big)\big(1+u_2+\cdots+u_{2k}\big),$$

where $u_j = t^j + t^{-j}$, and the result follows. □Theorem 4.6 implies both Murasugi and

Hartley theorems for two-bridge knots.

Theorem 5.6 (Murasugi (1958), Hartley (1979)) *Let*

$$\Delta(t) = a_0 - a_1(t+t^{-1}) + a_2(t^2+t^{-2}) - \cdots + (-1)^n a_n(t^n+t^{-n}),\ a_n > 0$$

be the Alexander polynomial of a two-bridge knot. There exists an integer $k \leq n$ *such that* $a_0 = a_1 = \ldots = a_k > a_{k+1} > \ldots > a_n$.

Proof. Let K be a two-bridge knot and $\nabla(z) = \alpha_0 f_1 - \alpha_1 f_3 + \cdots + (-1)^n \alpha_n f_{2n+1}$ be its Conway polynomial written in the Fibonacci basis. By Theorem 4.6, $\alpha_n\alpha_k \geq 0$ for all k, and if $\alpha_i = 0$ for some i then $\alpha_j = 0$ for $j \leq i$.

Let $\Delta(t) = a_0 - a_1(t+t^{-1}) + a_2(t^2+t^{-2}) - \cdots + (-1)^n a_n(t^n+t^{-n}),\ a_n > 0$ be the Alexander polynomial of K. We have $\Delta(t) = \varepsilon\nabla(t^{1/2}-t^{-1/2})$, where $\varepsilon = \pm 1$, and then, by Corollary 5.2, $\varepsilon\alpha_k = a_k - a_{k+1}$. We deduce that $\varepsilon\alpha_n = a_n > 0$, and then $a_k - a_{k+1} = \varepsilon\alpha_k \geq 0$ for all k. Consequently we obtain $a_0 \geq a_1 \geq \ldots \geq a_n > 0$.

Furthermore, if $a_k = a_{k-1}$ for some k, then $\alpha_{k-1} = 0$, and consequently $\alpha_{j-1} = 0$ for all $j \leq k$. This implies that for all $j \leq k$, $a_j = a_{j-1}$, which concludes the proof. □

Now, we shall give explicit formulas for Alexander coefficients in terms of Conway coefficients.

Proposition 5.7. *Let $Q(z) = \tilde{c}_0 + \tilde{c}_1 z^2 + \cdots + \tilde{c}_n z^{2n}$ be a polynomial. We have*

$$Q(t^{1/2} - t^{-1/2}) = a_0 - a_1(t + t^{-1}) + a_2(t^2 + t^{-2}) - \cdots + (-1)^n a_n(t^n + t^{-n}),$$

where

$$a_{n-j} = \sum_{k=0}^{j} (-1)^{n-k} \tilde{c}_{n-k} \tbinom{2n-2k}{j-k}. \tag{8}$$

Proof. It is sufficient to prove Formula (8) for the monomials $Q(z) = z^{2m}$. Let us consider $u_i = t^i + t^{-i}$. By the binomial formula we have

$$\left(t^{1/2} - t^{-1/2}\right)^{2m} = \sum_{k=0}^{m-1} (-1)^k \tbinom{2m}{k} u_{m-k} + (-1)^m \tbinom{2m}{m}.$$

and then $a_{n-j} = (-1)^m \binom{2m}{h}$ where $m - h = n - j$. On the other hand, the proposed formula asserts

$$a_{n-j} = \sum_{k=0}^{j} (-1)^{n-k} \tilde{c}_{n-k} \tbinom{2n-2k}{j-k} = (-1)^m \tbinom{2m}{h} \quad \text{where} \quad h = m + j - n,$$

which is the same result. □

Remark 5.8. Considering the Fibonacci polynomials $f_{2n+1} = \sum_{k=0}^{n} \binom{2n-k}{k} z^{2n-2k}$, Formulas (7) and (8) give the identity

$$1 = \sum_{k=0}^{j} (-1)^k \tbinom{2n-k}{k} \tbinom{2n-2k}{j-k},\ n, j \geq 0.$$

Remark 5.9. Fukuhara [6] gives a converse formula for the c_k in terms of the a_k,

$$\tilde{c}_{n-j} = \sum_{k=0}^{j} (-1)^{n-k} a_{n-k} \tfrac{2n-2k}{2n-j-k} \tbinom{2n-j-k}{2n-2j}.$$

From the bounds we obtained for Conway coefficients we can deduce a simple proof of the Nakanishi–Suketa bounds ([23, Th. 1, 2]) for the Alexander coefficients.

Theorem 5.10 (Nakanishi–Suketa (1993)) *We have the following sharp inequalities (where all the a_i are positive):*

1. $a_{n-j} \leq a_n \left(\sum_{k=0}^{j} \binom{2n-2k}{j-k} \binom{2n-k}{k} \right)$.

2. $2a_n - 1 \leq a_{n-1} \leq (4n-2)a_n + 1$.

Proof.

1. Using Formula (8) and Theorem 4.1, we obtain

$$|a_{n-j}| \leq \sum_{k=0}^{j} |\tilde{c}_{n-k}| \binom{2n-2k}{j-k} \leq |a_n| \sum_{k=0}^{j} \binom{2n-k}{k} \binom{2n-2k}{j-k}. \tag{9}$$

2. We have $|\tilde{c}_{n-1}| \leq \binom{2n-2}{1} |\tilde{c}_n| + 1$ by Theorem 4.4, and $a_{n-1} = \tilde{c}_{n-1} - \binom{2n}{1}\tilde{c}_n$ by Proposition 5.7. We thus deduce

$$|a_{n-1}| \leq \binom{2n}{1} |\tilde{c}_n| + \binom{2n-2}{1} |\tilde{c}_n| + 1 = (4n-2)\,|a_n| + 1. \tag{10}$$

We also have

$$|a_{n-1}| \geq \binom{2n}{1} |\tilde{c}_n| - |\tilde{c}_{n-1}| \geq \binom{2n}{1} |\tilde{c}_n| - \binom{2n-2}{1} |\tilde{c}_n| - 1 = 2\,|a_n| - 1.$$

The upper bounds (9) and (10) are attained by the knots $C(2, 2, \ldots, 2)$. □

We also have the following sharp bound, which improves the Nakanishi–Suketa third bound ([23, Th. 3])

Theorem 5.11. *If $a_n \neq 1$, then $a_{n-2} \leq (8n^2 - 15n + 8)a_n + 2n - 1$. This bound is sharp.*

Proof. From Proposition 5.7 and Theorem 4.4, we get

$$\begin{aligned} |a_{n-2}| &\leq \binom{2n}{2} |\tilde{c}_n| + \binom{2n-2}{1} |\tilde{c}_{n-1}| + \binom{2n-4}{0} |\tilde{c}_{n-2}| \\ &\leq \binom{2n}{2} |\tilde{c}_n| + \binom{2n-2}{1}\left(\binom{2n-2}{1} |\tilde{c}_n| + 1\right) + \left(\binom{2n-3}{2} + \tfrac{1}{g}\left(\binom{2n-3}{1} - 1\right)\right) |\tilde{c}_n| + 1 \\ &= (8n^2 - 16n + 10 + \tfrac{2(n-2)}{g})\,|a_n| + 2n - 1. \end{aligned}$$

If $a_n \neq 1$ then $g \geq 2$, and we obtain

$$|a_{n-2}| \leq |a_n|\,(8n^2 - 15n + 8) + 2n - 1. \tag{11}$$

This bound is attained for the knot $C(4, 2, 2, 2, \ldots, 2)$. □

Example 5.12. Let us consider the Conway polynomial $\nabla_K(z) = 1 + 8z^2 + 3z^4 - z^6$ of the knot $K = 13n1862$ (see [1]). It does not verify the bounds of theorem 4.1, and then it is not a two-bridge knot. Nevertheless, its Alexander polynomial $\Delta_K(t) = 23 - 19(t + 1/t) + 9(t^2 + 1/t^2) - (t^3 + 1/t^3)$ satisfies the bounds of Nakanishi and Suketa, and also the conditions of Murasugi and Hartley. This example shows that the conditions on the Conway coefficients are stronger than the conditions on the Alexander coefficient deduced from them.

Remarks 5.13.

1. If $g \geq 3$, the inequality (11) can be improved:
$$a_{n-2} \leq (8n^2 - 16n + 10 + \tfrac{2(n-2)}{g})a_n + 2n - 1.$$
2. For $j = 3$ we obtain
$$\begin{aligned} a_{n-3} &\leq 2/3\ (2\,n-3)\left(8\,n^2 - 24\,n + 25\right) a_n + \tfrac{(3\,n-5)(2\,n-5)}{g} a_n + n\,(2\,n-3) \\ &\leq 1/6\ \left(64\,n^3 - 270\,n^2 + 413\,n - 225\right) a_n + n\,(2\,n-3)\,. \end{aligned}$$
3. Since the inequalities on Conway coefficients are simpler and stronger, we shall not give the inequalities on Alexander coefficients for $j \geq 4$. Furthermore, if we want to apply our bounds to the Alexander polynomials, we first compute
$$\tilde{c}_{n-j} = \sum_{k=0}^{j} (-1)^{n-k} a_{n-k} \tfrac{2n-2k}{2n-j-k} \tbinom{2n-j-k}{2n-2j},$$
using Remark 5.9 and test if $|\tilde{c}_{n-j}| \leq \binom{2n-j}{j} |\tilde{c}_n|$, which is stronger than the inequality (9), or if $|\tilde{c}_{n-j}| \leq \left(\binom{2n-j-1}{j} + \frac{1}{g}\left(\binom{2n-j-1}{j-1} - 1\right)\right) |c_n| + 1$. The cost of these evaluations is less than the cost of the evaluations of the inequalities of Theorem 5.10. They are also sharper.

The following example shows an infinite family of polynomials satisfying all the necessary conditions except the equality case of Theorem 4.1.

Example 5.14. Consider the polynomial $P(z) = f_{m+1}(z) - 2dz^2,\ m = 4n \geq 4,\ d \neq 0$. All its coefficients, except one, satisfy $c_{m-2k} = \binom{m-k}{k}$. By Theorem 4.1, it is not the Conway polynomial of a two-bridge knot. Hence, the corresponding Alexander polynomial
$$\Delta(t) = 4d + 1 - (2d+1)u_1 + u_2 - u_3 + \cdots + u_{2n},$$
where $u_i = t^i + t^{-i}$, is not the Alexander polynomial of a two-bridge knot. Nevertheless, it satisfies all the necessary conditions of Hartley and Murasugi. If $0 < d < \frac{1}{2}n(n+1)$, it also satisfies the bounds of Theorems 4.1 and 4.4, and then the Nakanishi–Suketa bounds.

6 Conjectures

We observed a trapezoidal property for the Conway polynomials of two-bridged links with 20 or fewer crossings (their number is 131 839).

Conjecture 6.1. *Let* $\nabla_m = c_m\left(\sum_{i=0}^{\lfloor \frac{m}{2} \rfloor} (-1)^i \alpha_i f_{m+1-2i}\right),\ \alpha_0 = 1,$ *be the Conway polynomial of a two-bridge link (or knot) written in the Fibonacci basis. Then there exists* $n \leq \lfloor \frac{m}{2} \rfloor$ *such that*
$$0 \leq \alpha_0 \leq \alpha_1 \leq \cdots \leq \alpha_n, \quad \alpha_n \geq \alpha_{n+1} \geq \cdots \geq \alpha_{\lfloor \frac{m}{2} \rfloor} \geq 0.$$

If this conjecture was true, it would imply the following property of Alexander polynomials:

Conjecture 6.2. *Let* $\Delta(t) = a_0 - a_1(t+t^{-1}) + a_2(t^2+t^{-2}) - \cdots + (-1)^n a_n(t^n+t^{-n})$ *be the Alexander polynomial of a two-bridge knot. Then there exists an integer* $k \leq n$ *such that* $(a_0, \ldots, a_k)$ *is convex and* $(a_k, \ldots, a_n)$ *is concave.*

It is shown in [23] that the sequence a_j is not convex.

The following conjecture is attributed to Hoste:

Conjecture 6.3 (Hoste) *If* $z \in \mathbf{C}$ *is a root of the Alexander polynomial of an alternating knot, then* $\operatorname{Re} z > -1$.

This conjecture is shown to be true in some peculiar cases (see [19, 28]). As a direct consequence of the definition of Euler continuant polynomials, we show that:

Theorem 6.4. *Let* K *be a two-bridge link (or knot). Let* α *be a root of the Alexander polynomial* Δ_K*, then* $-\dfrac{3}{2} < \operatorname{Re}\alpha < 3 + 2\sqrt{2}$*. If* α *is real then* $3 - 2\sqrt{2} < \alpha < 3 + 2\sqrt{2}$.

Proof. Let K be a two-bridge link. ∇_K is an Euler continuant polynomial $D_m(b_1, \ldots, b_m)$. If z is a root of ∇_K, then the determinant in Formula (1) is equal to 0. It is a classical result in linear algebra that there exists i such that $|b_i z| < 2$. We thus deduce that $|z| < 2$.

Let α be a root of Δ_K. Then $z = \alpha^{1/2} - \alpha^{-1/2}$ is a root of ∇_K and we have the relation $P(\alpha, z) = \alpha^2 - (z^2+2)\alpha + 1 = 0$. Eliminating z between P and $|z| < 2$, we obtain that $\alpha = x + iy$ satisfies $R(x, y) < 0$ where

$$R = x^4 + 2\,x^2y^2 + y^4 - 4\,x^3 - 4\,xy^2 - 10\,x^2 - 14\,y^2 - 4\,x + 1.$$

An easy computation shows that the curve $R = 0$ has vertical tangents at the four points:

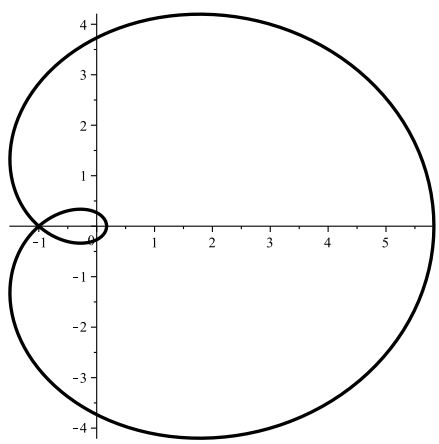

Figure 3: Region ($R < 0$) containing the roots of Alexander polynomials of two-bridge links.

$$(-\frac{3}{2}, \pm\frac{\sqrt{7}}{2}),\ (3 \pm 2\sqrt{2}, 0).$$

Suppose that α is real. Then $z^2 = \alpha + 1/\alpha - 2$ is real and $\mathrm{Discr}(P) = z^2(z^2+4) \geq 0$. We thus deduce that z is real and belongs to $(-2, 2)$. We thus have $\alpha \in (3 - 2\sqrt{2}, 3 + 2\sqrt{2})$. $\square$

This result is an improvement of those obtained in [19]. We found that it was independently obtained by Stoimenow (see [29]). It should be improved by a careful study of the tridiagonal matrix A_m in Formula (1).

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