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Article

Calculating Generators of Power Integral Bases in Sextic Fields with a Quadratic Subfield: The General Case

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Abstract

In some previous works we gave algorithms for determining generators of power integral basis in sextic fields with a quadratic subfield, under certain restrictions. The purpose of the present paper is to extend those methods to the general case, when the relative integral basis of the sextic field over the quadratic subfield is of general form. This raises several technical difficulties, that we consider here.

Keywords: monogeneity; power integral basis; sextic fields; relative cubic extension; quadratic subfield; Thue equations

MSC: 11Y50; 11R04; 11D25

1. Introduction

Monogeneity and power integral bases is a classical topic in algebraic number theory, which is intensively studied even today, see [1] for classical results, [2,3] for more recent results.

A number field K of degree n with ring of integers $\mathbb{Z}_K$ is called *monogenic* (cf. [2]) if there exists $\xi \in \mathbb{Z}_K$ such that $(1, \xi, \dots, \xi^{n-1})$ is an integral basis, called *power integral basis*. We call ξ the *generator* of this power integral basis.

An irreducible polynomial $f(x) \in \mathbb{Z}[x]$ is called *monogenic*, if a root ξ of $f(x)$ generates a power integral basis in $K = \mathbb{Q}(\xi)$. If $f(x)$ is monogenic, then K is also monogenic, but the converse is not true.

For $\alpha \in \mathbb{Z}_K$ (generating K over $\mathbb{Q}$) the module index

$$I(\alpha) = (\mathbb{Z}_K : \mathbb{Z}[\alpha])$$

is called the *index* of α . The element α generates a power integral basis in K if and only if $I(\alpha) = 1$. Searching for elements of $\mathbb{Z}_K$, generating power integral bases, leads to a Diophantine equation, called *index form equation* (cf. [2]).

There are certain algorithms to determine "all solutions" of these equations, that is all generators of power integral bases. This "complete resolution" requires very often too long CPU time. On the other hand there are some very fast methods for determining generators of power integral bases with "small" coefficients, say, being $< 10^{100}$ in absolute value, with respect to an integral basis. All our experiences show that generators of power integral bases have very small coefficients in the integral basis, therefore these "small" solutions cover all solutions with high probability, certainly all generators that can be used in practice for further calculations. It is usual to apply such algorithms also if we need to solve a large number of equation (cf. [2]).

In sextic fields with a quadratic subfield we developed some efficient methods for calculating "small" solutions of the index form equation, see [4,5]. For simplicity, in these results we assumed, that the basis of the sextic field is of special type

$$(1, \alpha, \alpha^2, \omega, \omega\alpha, \omega\alpha^2),$$

where $(1, \omega)$ is an integral basis of the quadratic subfield. This implicitly yields, that the sextic field apriori has a relative power integral basis over the quadratic subfield. In the present paper we extend this special case to the general case, when the relative integral basis is of arbitrary form.

This paper was initiated by the recent work of Harrington and Jones [6], where they consider sextic trinomials of the form $f(x) = x^6 + ax^3 + b$. Considering the sextic fields in [6], generated by a root of such a trinomial, we find that in most cases the root of the polynomial does not generate a power integral basis over the quadratic subfield. In the present paper we intend to give a fast algorithm to calculate "small" solutions of the index form equation in such sextic fields. We shall see, that some crucial ingredients of the method are similar to the formerly considered simpler cases, however several complications occur that make it worthy to provide a description in the general case. In other words, we describe how the previous algorithms can be extended to the general case. Also, note that the present method can be easily transformed to a process to calculate "all" solutions.

2. Sextic Fields with a Quadratic Subfield

Let M be a quadratic number field with integral basis $(1, \omega)$, and let $f(x) = x^3 + C_2x^2 + C_1x + C_0 \in \mathbb{Z}_M[x]$ be the relative defining polynomial of α over M , with $K = M(\alpha)$. For sextic fields with a quadratic subfield a crucial step, the reduction, only works for complex quadratic subfields, therefore we assume that M is complex.

We are going to determine generators of power integral bases of K .

To present our formulas explicitly we write the relative integral basis of K over M in the form

$$\left(1, \frac{A\alpha + B}{k}, \frac{C\alpha^2 + D\alpha + E}{\ell}\right), \quad (1)$$

where $A, B, C, D, E \in \mathbb{Z}_M$, $0 < k, \ell \in \mathbb{Z}$. Note that if K is (absolute) monogenic, then it is also relative monogenic over M , implying that K has a relative integer basis over M .

Using the relative integral basis (1) we can represent any $\gamma \in \mathbb{Z}_K$ in the form

$$\gamma = X_0 + X_1 \frac{A\alpha + B}{k} + X_2 \frac{C\alpha^2 + D\alpha + E}{\ell}, \quad (2)$$

with unknown $X_i = x_{i1} + \omega x_{i2} \in \mathbb{Z}_M$ ($i = 0, 1, 2$). Our purpose is to construct a fast algorithm to determine all tuples $(x_{02}, x_{11}, x_{12}, x_{21}, x_{22}) \in \mathbb{Z}^5$ with

$$\max(|x_{02}|, |x_{11}|, |x_{12}|, |x_{21}|, |x_{22}|) < C, \quad (3)$$

with say, $C = 10^{100}$, such that γ generates a power integral basis in K (the index of γ is independent from x_{01}).

We have

$$\gamma = Y_0 + Y_1\alpha + Y_2\alpha^2,$$

where

$$Y_0 = X_0 + X_1 \frac{B}{k} + X_2 \frac{E}{\ell}, \quad Y_1 = X_1 \frac{A}{k} + X_2 \frac{D}{\ell}, \quad Y_2 = X_2 \frac{C}{\ell}, \quad (4)$$

are not necessarily integer elements in M .

Let $\mu^{(i)}$ be the conjugates of any $\mu \in M$, corresponding to $\omega^{(i)}$, ($i = 1, 2$). We denote by $\alpha^{(i,j)}$ the roots of $f^{(i)}(x) = x^3 + C_2^{(i)}x^2 + C_1^{(i)}x + C_0^{(i)}$, ($i = 1, 2, j = 1, 2, 3$). The conjugates of any $\mu \in K$ corresponding to $\alpha^{(i,j)}$ will also be denoted by $\mu^{(i,j)}$.

For $i = 1, 2, 1 \leq j_1, j_2 \leq 3, j_1 \neq j_2$ we have

$$\frac{\gamma^{(i,j_1)} - \gamma^{(i,j_2)}}{\alpha^{(i,j_1)} - \alpha^{(i,j_2)}} = Y_1 + (\alpha^{(i,j_1)} + \alpha^{(i,j_2)})Y_2 = Y_1 - \delta^{(i,j_3)} Y_2,$$

where $-\delta^{(i,j_3)} = \alpha^{(i,j_1)} + \alpha^{(i,j_2)} = -C_2^{(i)} - \alpha^{(i,j_3)}$, $C_2 \in \mathbb{Z}_M$ being the quadratic coefficient of the relative defining polynomial $f(x)$ of α over M , and $\{j_3\} = \{1, 2, 3\} \setminus \{j_1, j_2\}$.

By the representation (1) of the relative integral basis of K over M , for the relative discriminant $D_{K/M}$ we have

$$N_{M/\mathbb{Q}}(D_{K/M}) = \frac{N_{M/\mathbb{Q}}(d_{K/M}(\alpha))}{(k\ell)^2} = \frac{1}{(k\ell)^2} \prod_{i=1}^2 \prod_{1 \leq j_1 < j_2 \leq 3} \left(\alpha^{(i,j_1)} - \alpha^{(i,j_2)} \right)^2.$$

Therefore we obtain

$$\begin{aligned} I_{K/M}(\gamma) &= \frac{1}{\sqrt{|N_{M/\mathbb{Q}}(D_{K/M})|}} \prod_{i=1}^2 \prod_{1 \leq j_1 < j_2 \leq 3} \left| \gamma^{(i,j_1)} - \gamma^{(i,j_2)} \right| \\ &= (k\ell) \prod_{i=1}^2 \prod_{j=1}^3 \left| Y_1^{(i)} - \delta^{(i,j)} Y_2^{(i)} \right| = (k\ell) |N_{M/\mathbb{Q}}(N_{K/M}(Y_1 - \delta Y_2))|. \end{aligned} \quad (5)$$

As it is known (see [2], Chapter 1, Theorem 1.6), if $I(\gamma) = 1$, then both

$$I_{K/M}(\gamma) = 1, \text{ and } J(\gamma) = 1,$$

where

$$J(\gamma) = \frac{1}{(\sqrt{|D_M|})^3} \prod_{j_1=1}^3 \prod_{j_2=1}^3 \left| \gamma^{(1,j_1)} - \gamma^{(2,j_2)} \right|. \quad (6)$$

3. Elementary Estimates

By $I_{K/M}(\gamma) = 1$, (5) implies

$$N_{M/\mathbb{Q}}(N_{K/M}(Z_1 - \delta Z_2)) = \pm (k\ell)^5, \quad (7)$$

where

$$Z_1 = (k\ell)Y_1, \quad Z_2 = (k\ell)Y_2 \in \mathbb{Z}_M. \quad (8)$$

Using an algebraic number theory package like Magma or Kash we can determine a complete set of non-associated elements $\mu \in \mathbb{Z}_M$ of norm $\pm(k\ell)^5$. Let ε be one of the finitely many units in M . We confer

$$N_{K/M}(Z_1 - \delta Z_2) = \varepsilon \mu, \quad (9)$$

with certain possible values of μ, ε . In complex quadratic fields the conjugated elements have equal absolute values, therefore (9) implies

$$\prod_{j=1}^3 \left| Z_1^{(1)} - \delta^{(1,j)} Z_2^{(1)} \right| = |k\ell|^{5/2}. \quad (10)$$

Denote by j_0 the conjugate with

$$\left| Z_1^{(1)} - \delta^{(1,j_0)} Z_2^{(1)} \right| = \min_{1 \leq j \leq 3} \left| Z_1^{(1)} - \delta^{(1,j)} Z_2^{(1)} \right|.$$

Then

$$\left| Z_1^{(1)} - \delta^{(1,j_0)} Z_2^{(1)} \right| \leq c_1 \quad (11)$$

with $c_1 = |k\ell|^{5/6}$, and for $j \neq j_0$ we have

$$\left| Z_1^{(1)} - \delta^{(1,j)} Z_2^{(1)} \right| \geq \left| \delta^{(1,j)} - \delta^{(1,j_0)} \right| \left| Z_2^{(1)} \right| - c_1 \geq c_2 \left| Z_2^{(1)} \right|, \quad (12)$$

with $c_2 = 0.9 \cdot \min_{j \neq j_0} |\delta^{(1,j)} - \delta^{(1,j_0)}|$, if $|Z_2^{(1)}| > 10c_1 / \min_{j \neq j_0} |\delta^{(1,j)} - \delta^{(1,j_0)}|$. Small coordinates of Z_2 , not satisfying this inequality are tested separately.

We set $Z_1 = z_{11} + \omega z_{12}$, $Z_2 = z_{21} + \omega z_{22}$ with $z_{11}, z_{12}, z_{21}, z_{22} \in \mathbb{Z}$ and let

$$A = \max(|z_{11}|, |z_{12}|, |z_{21}|, |z_{22}|).$$

Note that to find all suitable $(x_{02}, x_{11}, x_{12}, x_{21}, x_{22}) \in \mathbb{Z}^5$ satisfying (3), in view of (4), (8) we have to consider all $(z_{11}, z_{12}, z_{21}, z_{22})$ with

$$A \leq 6(k\ell)C(1 + \overline{|\omega|}) \max\left(1, \frac{B}{k}, \frac{E}{\ell}, \frac{A}{k}, \frac{D}{\ell}, \frac{C}{\ell}\right). \quad (13)$$

(11) implies

$$\max(|z_{11}|, |z_{12}|) \leq 2|Z_1^{(1)}| \leq 2(c_1 + \overline{|\delta|} |Z_2^{(1)}|) \leq 2(0.1 + \overline{|\delta|}) |Z_2^{(1)}|,$$

if $0.1|Z_2^{(1)}| > c_1$ (small coordinates of Z_2 are tested separately). Here $\overline{|\delta|}$ is the size δ (the maximum absolute values of its conjugates). Similarly $\max(|z_{21}|, |z_{22}|) \leq 2|Z_2^{(1)}|$, therefore

$$A \leq 2(0.1 + \overline{|\delta|}) |Z_2^{(1)}|.$$

By (10) and (12) we obtain

$$\left| Z_1^{(1)} - \delta^{(1,j_0)} Z_2^{(1)} \right| \leq \frac{(k\ell)^{5/2}}{c_2^2} |Z_2^{(1)}|^{-2} \leq c_4 A^{-2},$$

with

$$c_4 = \frac{(k\ell)^{5/2}}{4c_2^2(0.1 + \overline{|\delta|})^2},$$

whence

$$\left| z_{11} + \omega^{(1)} z_{12} - \delta^{(1,j_0)} z_{21} - \delta^{(1,j_0)} \omega^{(1)} z_{22} \right| \leq c_4 A^{-2}. \quad (14)$$

4. Reduction

The reduction procedure is based on inequality (14). The bound in (13) is reduced in several consecutive steps. We start with $A_0 = A_{\max}$, $A_{\max}$ being the bound in (13). We assign a suitable large constant H , perform the following reduction step, which produces a new bound for A . We set this new bound in place of A_0 and continue the reduction until the reduced bound is smaller than the original one.

Consider the lattice generated by the columns of the matrix

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ H & H\Re(\omega^{(1)}) & \Re(-\delta^{(1,j_0)}) & H\Re(-\delta^{(1,j_0)}\omega^{(1)}) \\ 0 & H\Im(\omega^{(1)}) & H\Im(-\delta^{(1,j_0)}) & H\Im(-\delta^{(1,j_0)}\omega^{(1)}) \end{pmatrix}.$$

Denote by b_1 the first vector of the LLL reduced basis of this lattice. According to Lemma 5.3 of [2] (which statement is based on (14)), if $A \leq A_0$ and H is large enough to have

$$|b_1| \geq \sqrt{40} \cdot A_0, \quad (15)$$

then

$$A \leq \left(\frac{c_4 \cdot H}{A_0}\right)^{1/2}.$$

For a certain A_0 the suitable H is of magnitude A_0^2 . A typical sequence of reduced bounds starting from $A_0 = 10^{100}$ was the following:

A	10^{100}	$1.5805 \cdot 10^{51}$	$6.2833 \cdot 10^{26}$	$1.2528 \cdot 10^{15}$
H	10^{202}	$2.4979 \cdot 10^{104}$	$3.9481 \cdot 10^{55}$	$1.5695 \cdot 10^{32}$
new A	$1.5805 \cdot 10^{51}$	$6.2833 \cdot 10^{26}$	$1.2528 \cdot 10^{15}$	$5.5942 \cdot 10^8$

A	$5.5942 \cdot 10^8$	$3.7382 \cdot 10^5$	8663	1553
H	$3.1295 \cdot 10^{19}$	$1.3974 \cdot 10^{13}$	$9.3381 \cdot 10^9$	$2.4139 \cdot 10^8$
new A	$3.7382 \cdot 10^5$	8663	1553	622

A	622	394	313	280
H	$3.8810 \cdot 10^7$	$1.5562 \cdot 10^7$	$9.8543 \cdot 10^6$	$7.8416 \cdot 10^6$
new A	394	313	280	264

If in a certain step H was not sufficiently large, we replaced it by $10H$. The reduction procedure was executed with 250 digits accuracy and took only a few seconds. It has to be performed for each possible values of j_0 , and the final reduced bound for A is the maximum of the reduced bounds obtained for $j_0 = 1, 2, 3$.

5. Enumeration, Test

The reduced bound obtained in the previous section gives an upper bound among others for $|z_{11}|, |z_{12}|$, hence we can enumerate all possible Z_1 . Further, for all possible ε, μ , equation (9) gives a cubic equation for $Z_2 \in \mathbb{Z}_M$. Testing the roots of this cubic equation in Z_2 we can determine all $Z_2 \in \mathbb{Z}_M$ corresponding to Z_1 . From (8) and (4) we can determine Y_1, Y_2 and then the coordinates x_{11}, x_{12} and x_{21}, x_{22} of X_1, X_2 , corresponding to Z_1, Z_2 . Finally, we use (6) to determine x_{02} in the representation (2) of γ (the index of γ is independent of x_{01}). Substituting the possible tuples $x_{11}, x_{12}, x_{21}, x_{22}$ into $J(\gamma)$ we obtain a polynomial $F(x) = a_9x^9 + \dots + a_1x + a_0$ in x_{02} of degree 9, such that

$$|F(x_{02})| = 1.$$

For the roots x_{02} of absolute value >1 we have

$$|x_{02}| \leq \frac{|a_8| + \dots + |a_1| + |a_0| + 1}{|a_9|}.$$

We test the possible integer values of x_{02} and obtain the solutions. Note that x_{11}, x_{12} and x_{21}, x_{22} are usually small values, therefore the bound for $|x_{02}|$ is also reasonably small.

6. Example

We developed and tested our method by taking the trinomial

$$f(x) = x^6 + 3x^3 + 9$$

with Galois group $C_3 \times S_3$ from the paper [6] of Harrington and Jones. These trinomials have several interesting features, which may be the topic of a separate paper. This polynomial is not monogenic, but the number field K generated by a root α of it is monogenic.

The quadratic subfield of K is determined by the equation $x^2 + 3x + 9 = 0$. It's root is $\beta = (-3 + 3i\sqrt{3})/2$, therefore $M = \mathbb{Q}(i\sqrt{3})$. We set $\omega = (1 + i\sqrt{3})/2$, then $\beta = 3\omega - 3$ and $\alpha = \sqrt[3]{\beta}$. A relative integers basis of $K = \mathbb{Q}(\alpha)$ over $\mathbb{Q}$ is given by

$$\left(1, \alpha, \frac{\alpha^2(1 + \omega)}{3}\right).$$

We have

$$\gamma = X_0 + X_1\alpha + X_2\frac{\alpha^2(1 + \omega)}{3} = Y_0 + Y_1\alpha + Y_2\alpha^2,$$

with

$$Y_0 = X_0, Y_1 = X_1, Y_2 = X_2\frac{1 + \omega}{3}.$$

Moreover, $\delta = \alpha, k = 1, \ell = 3$,

$$3 \cdot N_{M/\mathbb{Q}}(N_{K/M}(Y_1 - \delta Y_2)) = \pm 1,$$

and

$$N_{M/\mathbb{Q}}(N_{K/M}(Z_1 - \delta Z_2)) = \pm 3^5$$

with $Z_1 = 3Y_1, Z_2 = 3Y_2$, whence

$$|Z_1^3 - \beta Z_2^3| = |N_{K/M}(Z_1 - \delta Z_2)| = 3^{5/2}.$$

Taking $C = 10^{100}$ we have to reduce A from $24C$. The reduction procedure gives a bound 250 for the absolute values of the coordinates $z_{11}, z_{12}, z_{21}, z_{22}$. In our case Y_1 is also integer, hence z_{11}, z_{12} are divisible by 3, which considerably reduces the number of possible pairs z_{11}, z_{12} .

We used Magma to calculate the elements in $\mathbb{Z}_M$ of norm $\pm 3^5$. It turned out that up to associates the only such element is $9 - 18\omega$. We set $\varepsilon = \pm 1, \frac{\pm 1 \pm i\sqrt{3}}{2}$ and used

$$Z_1^3 - \beta Z_2^3 = \varepsilon \mu$$

to determine the possible values of Z_1 , corresponding to Z_2 . Finally, we calculate Y_1, Y_2 , then X_1, X_2 and substituted the coordinates of X_1, X_2 into $J(\gamma) = 1$ to determine the appropriate values of x_{02} . We obtained that up to sign the solutions are:

x_{02}	x_{11}	x_{12}	x_{21}	x_{22}
-1	0	1	0	-1
1	1	0	1	-1
0	0	0	-1	1
0	0	0	0	-1
0	0	0	1	0
-1	1	-1	1	0

That is, up to sign and translation by x_{01} all generators of power integral bases of K are given by

$$\gamma = \omega x_{02} + (x_{11} + \omega x_{12})\alpha + (x_{21} + \omega x_{22})\frac{\alpha^2(1 + \omega)}{3},$$

with the above listed tuples $(x_{02}, x_{11}, x_{12}, x_{21}, x_{22})$.

All calculations were performed in Maple and took just a few seconds.

7. Conclusions

There are several results on monogeneity or non-monogeneity of wide classes of number fields even for high degrees. However, to determine explicitly all generators of power integral bases in a

specific number field turns out to be a much more complicated problem. We try to extend the methods of existing algorithms to some more general cases. In this paper, it is done for sextic fields with a quadratic subfield, without the previous assumption of having a special type of relative integral basis.

Conflicts of Interest: The author has no competing interests to declare that are relevant to the content of this article.

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