

Research Article

On the Common Index Divisors of a Dihedral Field of Prime Degree

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A criterion for a prime to be a common index divisor of a dihedral field of prime degree is given. This criterion is used to determine the index of families of dihedral fields of degrees 5 and 7.

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1. Introduction

Let L be an algebraic number field of degree n . Let O_L denote the ring of integers of L . The element $\alpha \in O_L$ is called a generator of L if $L = \mathbb{Q}(\alpha)$. The index of α is the positive integer $\text{ind } \alpha$ given by

$$D(\alpha) = (\text{ind } \alpha)^2 d(L), \quad (1.1)$$

where $d(L)$ is the discriminant of L and $D(\alpha)$ is the discriminant of the minimal polynomial of α . The index of L is

$$i(L) = \gcd \{ \text{ind } \alpha \mid \alpha \text{ is a generator of } L \}. \quad (1.2)$$

A positive integer > 1 dividing $i(L)$ is called a common index divisor of L . If O_L possesses an element β such that $\{1, \beta, \beta^2, \dots, \beta^{n-1}\}$ is an integral basis for L , then L is said to be monogenic. If L is monogenic, then $i(L) = 1$. Thus a field possessing a common index divisor is nonmonogenic.

Let $f(x)$ be an irreducible polynomial in $\mathbb{Z}[x]$ of odd prime degree q and suppose that $\text{Gal}(f(x)) \simeq D_q$ (the dihedral group of order $2q$). We note that $D_q = \langle \sigma, \tau \rangle$ with $\sigma^q = \tau^2 = (\sigma\tau)^2 = 1$. Let M be the splitting field of $f(x)$. Let θ be a root of $f(x)$ and set

$L = \mathbb{Q}(\theta)$ so that the degree of L over \mathbb{Q} is equal to q . We denote the unique quadratic subfield of M by K .

We prove in Section 2 the following theorem which gives a criterion for a prime p to be a common index divisor of L .

THEOREM 1.1. *Let $f(x) \in \mathbb{Z}[x]$ be irreducible, $\deg(f(x)) = q$ (an odd prime), and $\text{Gal}(f(x)) \simeq D_q$. Let M be the splitting field of $f(x)$. Let $\theta \in \mathbb{C}$ be a root of $f(x)$. Set $L = \mathbb{Q}(\theta)$ so that $[L : \mathbb{Q}] = q$. Let K be the unique quadratic subfield of M . If p is a prime satisfying*

$$p < \frac{1}{2}(q + 1), \quad p \mid d(K), \tag{1.3}$$

then

$$p = R_1 R_2^2 \cdots R_{(q+1)/2}^2 \tag{1.4}$$

for distinct prime ideals $R_1, R_2, \dots, R_{(q+1)/2}$ of O_L , and p is a common index divisor of L .

As an application of Theorem 1.1, we determine in Section 3 the index of a field defined by a dihedral quintic trinomial of the form $x^5 + ax + b$, $a, b \in \mathbb{Z}$.

In Section 4, we determine the index of an infinite family of fields defined by dihedral polynomials of degree 7.

Finally in Section 5, we consider a dihedral field of degree 11 and use Theorem 1.1 to show that it is nonmonogenic.

We note that a method for calculating a generator of K , and hence $d(K)$, directly from $f(x)$ is given in [1].

2. Proof of Theorem 1.1

As $p \mid d(K)$, we have $p = \wp^2$ for some prime ideal \wp of O_K . Suppose that \wp is inert in M/K . Then $p = \wp^2$ in M/\mathbb{Q} . This contradicts [2, Theorem 10.1.26, part (6)]. Hence \wp is not inert in M/K . Suppose \wp totally ramifies in M/K . Then $\wp = Q^q$ for some prime ideal Q of M . Thus $p = \wp^2 = Q^{2q}$ in M . Hence, by [2, Theorem 10.1.26, part (9)], we have $p \mid q$. But p and q are primes so $p = q$. This contradicts the assumption $p < (1/2)(q + 1)$. Hence \wp does not totally ramify in M . Then, as M is normal over K of prime degree q , we have

$$\wp = Q_1 Q_2 \cdots Q_q \tag{2.1}$$

for distinct prime ideals Q_1, Q_2, \dots, Q_q of M . Thus

$$p = \wp^2 = Q_1^2 Q_2^2 \cdots Q_q^2. \tag{2.2}$$

Hence, by [2, Theorem 10.1.26, part (6)], we have

$$p = R_1 R_2^2 \cdots R_{(q+1)/2}^2 \tag{2.3}$$

for distinct prime ideals $R_1, R_2, \dots, R_{(q+1)/2}$ of L , which is (1.4). We note that the decomposition of p in L can be checked directly by studying the $\text{Gal}(M/L)$ action on the coset space D_q/D , where D is a decomposition subgroup at p .

Let $g(x)$ be any defining polynomial for L , so that $\deg(g(x)) = q$. Let ϕ be a root of $g(x)$ such that $\mathbb{Q}(\phi) = L$. Suppose $p \nmid \text{ind}(\phi)$. The inertial degree $f = 1$ in the extension M/\mathbb{Q} (using the tower $M/K/\mathbb{Q}$), hence in L/\mathbb{Q} , so that all the irreducible factors of $g(x)$ modulo p are linear. Thus $g(x)$ has at most p irreducible factors modulo p . Hence, by Dedekind's theorem, p factors into at most p prime ideals in L . Thus by (1.4) we have $(1/2)(q+1) \leq p$. This contradicts $p < (1/2)(q+1)$. Hence $p \mid \text{ind}(\phi)$ for all defining polynomials g . Thus p is a common index divisor of L .

3. Dihedral quintic trinomials

Let $f(x) = x^5 + ax + b \in \mathbb{Z}[x]$ have Galois group D_5 . Then there exist coprime integers m and n and $i, j \in \{0, 1\}$ such that

$$\begin{aligned} a &= 2^{2-4i}5^{1-4j}d_2(m^2 - mn - n^2)E^2F, \\ b &= 2^{4-5i}5^{-5j}d_1(2m - n)(m + 2n)E^3F, \end{aligned} \quad (3.1)$$

where d_1^2 is the largest square dividing $m^2 + n^2$, d_2^5 is the largest fifth power dividing $m^2 + mn - n^2$, and

$$E = \frac{m^2 + n^2}{d_1^2}, \quad F = \frac{m^2 + mn - n^2}{d_2^5}. \quad (3.2)$$

This result is due to Roland et al. [3, page 138], see also [4, page 139]. The discriminant of $x^5 + ax + b$ is

$$D(f) = 2^{16-20i}5^{6-20j}(2m^6 + 4m^5n + 5m^4n^2 - 5m^2n^4 + 4mn^5 - 2n^6)^2E^{10}F^4, \quad (3.3)$$

see [3, equation (3), page 139]. As $\gcd(m, n) = 1$, we have $3 \nmid m^2 + n^2$ and $3 \nmid m^2 + mn - n^2$ so $3 \nmid E$ and $3 \nmid F$. If $3 \mid n$, then $3 \mid m$, and so $3 \nmid 2m^6 + 4m^5n + 5m^4n^2 - 5m^2n^4 + 4mn^5 - 2n^6$. If $3 \nmid n$, then as the polynomial $2x^6 + 4x^5 + 5x^4 - 5x^2 + 4x - 2$ is irreducible (mod 3), we deduce that $3 \nmid 2m^6 + 4m^5n + 5m^4n^2 - 5m^2n^4 + 4mn^5 - 2n^6$. Hence $3 \nmid D(f)$. Thus $3 \nmid \text{ind}(\theta)$, where $L = \mathbb{Q}(\theta)$, $f(\theta) = 0$. Hence $3 \nmid i(L)$. By Engstrom [5, page 234] as $[L : \mathbb{Q}] = 5$, the only primes that can divide $i(L)$ are 2 and 3. We use our theorem to show that $2 \mid i(L)$. From Spearman and Williams [4, pages 149, 150], the discriminant $d(K)$ of the unique quadratic subfield of the splitting field of $f(x)$ satisfies

$$\begin{aligned} 2^2 \parallel d(K) & \quad \text{if } m \equiv n + 1 \pmod{2}, \\ 2^3 \parallel d(K) & \quad \text{if } m \equiv n \equiv 1 \pmod{2}. \end{aligned} \quad (3.4)$$

Thus $2 \mid d(K)$. Hence, by Theorem 1.1, 2 is a common index divisor of L . From Engstrom [5, Table, page 234], as $2 = R_1R_2^2R_3^2$ by Theorem 1.1, we deduce, $i(L) = 2$. As $i(L) \neq 1$, this gives an infinite family of nonmonogenic dihedral quintic fields. In [6], an infinite family of monogenic dihedral quintic fields was exhibited.

4. A class of dihedral polynomials of degree 7

We recall a family of polynomials of degree 7 due to Smith [7, page 790]. This family is $f_t(x)$ ($t \in \mathbb{Z}$), where $f_t(x)$ is given by

$$\begin{aligned}
 f_t(x) = x^7 - (7t^3 + 35t^2 + 21t + 1)[21x^5 + (98t + 70)x^4 \\
 - (1029t^3 + 4557t^2 + 343t - 105)x^3 \\
 - 28(7t + 1)(49t^3 + 147t^2 + 63t - 3)x^2 \\
 + 7(7t^2 + 42t - 1)(7t^2 + 14t - 5)(7t + 1)^2x \\
 + 235298t^7 + 1236858t^6 + 1138074t^5 \\
 + 562226t^4 + 11270t^3 - 4914t^2 - 322t + 6].
 \end{aligned} \tag{4.1}$$

Smith showed that the Galois group of $f_t(x)$ over $\mathbb{Q}(t)$ is D_7 . We are interested in determining integers t for which the Galois group of $f_t(x)$ (considered as a polynomial in $\mathbb{Z}[x]$) over \mathbb{Q} is D_7 . MAPLE gives the discriminant of $f_t(x)$ as

$$\begin{aligned}
 D(f_t) = 2^{46}7^{12}t^{15}(7t^2 - 14t - 9)^6(7t^3 + 35t^2 + 21t + 1)^6 \\
 \times (63t^2 + 266t - 25)^2(49t^4 - 196t^3 - 1694t^2 - 140t - 3)^2.
 \end{aligned} \tag{4.2}$$

LEMMA 4.1. (i) If $t \equiv 1 \pmod{3}$, then $3 \nmid D(f_t)$.
 (ii) If $t \equiv 1, 2 \text{ or } 4 \pmod{5}$, then $5 \nmid D(f_t)$.

The proof follows from (4.2).

LEMMA 4.2. If $t \in \mathbb{Z}$ is such that

$$2 \mid t, \quad 7t^3 + 35t^2 + 21t + 1 \text{ is square-free} > 1, \tag{4.3}$$

then $f_t(x)$ is irreducible over \mathbb{Q} .

Proof. Set $a(t) = 7t^3 + 35t^2 + 21t + 1$ and $b(t) = -235298t^7 - 1236858t^6 - 1138074t^5 - 562226t^4 - 11270t^3 + 4914t^2 + 322t - 6$. Then, from (4.1), we see that

$$f_t(x) \equiv x^7 \pmod{a(t)}, \tag{4.4}$$

$$f_t(0) = a(t)b(t). \tag{4.5}$$

The resultant of $a(t)$ and $b(t)$ as polynomials in t is (by MAPLE) $2^{45}7^7$. Clearly $7 \nmid a(t)$ and (as $2 \mid t$) $2 \nmid a(t)$. Thus $\gcd_{\mathbb{Z}}(a(t), b(t)) = 1$. Let q be any prime dividing $a(t)$ (so $q \neq 2, 7$). Then $q \parallel a(t)$ and $q \nmid b(t)$. Thus, by (4.1) and (4.4), q divides the coefficients of x^i ($i = 0, 1, 2, 3, 4, 5, 6$) in $f_t(x)$ and by (4.5) $q \parallel f_t(0)$. Hence, by Eisenstein's criterion, $f_t(x)$ is irreducible over \mathbb{Q} . □

Let θ denote one of the roots of $f_t(x)$. Let $\alpha_1 = \theta, \alpha_2, \dots, \alpha_7$ be all the roots of $f_t(x)$. Set $L = \mathbb{Q}(\theta)$. Under condition (4.3), we have $[L : \mathbb{Q}] = 7$.

LEMMA 4.3. For $t \in \mathbb{Z}$, set

$$P_{f_t}(x) = \prod_{1 \leq i < j \leq 7} (x - (\alpha_i + \alpha_j)). \quad (4.6)$$

Then $P_{f_t}(x) \in \mathbb{Z}[x]$ and

$$P_{f_t}(x) = F_t(x)G_t(x)H_t(x), \quad (4.7)$$

where $F_t(x)$, $G_t(x)$, and $H_t(x)$ are distinct polynomials of degree 7 in $\mathbb{Z}[x]$, which satisfy

$$\begin{aligned} F_t(x) &\equiv G_t(x) \equiv H_t(x) \equiv x^7 \pmod{a(t)}, \\ F_t(0) &= -32a(t)c(t), \\ G_t(0) &= -32a(t)d(t), \\ H_t(0) &= 32a(t)e(t), \end{aligned} \quad (4.8)$$

where

$$\begin{aligned} c(t) &= 27783t^6 + 43218t^5 - 300615t^4 + 131516t^3 + 17241t^2 - 14t - 25, \\ d(t) &= 8575t^6 - 52822t^5 + 34153t^4 + 27244t^3 + 2737t^2 - 406t - 25, \\ e(t) &= 1029t^6 - 4802t^5 - 9457t^4 - 5292t^3 - 973t^2 + 14t + 25. \end{aligned} \quad (4.9)$$

Proof. The assertion $P_{f_t}(x) \in \mathbb{Z}[x]$ follows from [8, Lemma 11.1.3, page 359] and the fact that $\alpha_1, \alpha_2, \dots, \alpha_7$ are algebraic integers. The remaining assertions of the lemma can be verified using MAPLE. \square

LEMMA 4.4. If $t \in \mathbb{Z}$ is such that

$$2 \mid t, \quad 7t^3 + 35t^2 + 21t + 1 \text{ is square-free} > 1 \quad (4.10)$$

then the polynomials $F_t(x)$, $G_t(x)$, and $H_t(x)$ are irreducible over \mathbb{Q} .

Proof. The resultants of $a(t)$ and $c(t)$ (resp., $a(t)$ and $d(t)$, $a(t)$ and $e(t)$) regarded as polynomials in t are by MAPLE $-2^{30}7^6$ (resp., $-2^{30}7^6$, $2^{30}7^6$). Exactly as in the proof of Lemma 4.2, making use of Lemma 4.3, we find by Eisenstein's criterion that the polynomials $F_t(x)$, $G_t(x)$, and $H_t(x)$ are irreducible over \mathbb{Q} . \square

LEMMA 4.5. *If $t \in \mathbb{Z}$ is such that*

$$\begin{aligned} 2 \mid t, \quad 7t^3 + 35t^2 + 21t + 1 \text{ is square-free} > 1, \\ t \text{ is not a perfect square,} \end{aligned} \tag{4.11}$$

then

$$\text{Gal}(f_t(x)) \simeq D_7. \tag{4.12}$$

Proof. Jensen and Yui [8, Theorem II.1.2, page 359] have shown that a monic polynomial $f(x) \in \mathbb{Q}[x]$ of degree p , where p is a prime $\equiv 3 \pmod{4}$, has $\text{Gal}(f) \simeq D_p$ if and only if

- (i) $f(x)$ is irreducible over \mathbb{Q} ,
- (ii) $D(f)$ is not a perfect square,
- (iii) $P_f(x)$ factors as a product of $(p - 1)/2$ distinct irreducible polynomials of degree p over \mathbb{Q} .

By Lemma 4.2, $f_t(x)$ is irreducible over \mathbb{Q} . As t is not a perfect square, we see by (4.2) that $D(f_t)$ is not a perfect square. Finally, by Lemmas 4.3 and 4.4, $P_{f_t}(x)$ factors as a product of 3 distinct irreducible polynomials of degree 7 over \mathbb{Q} . Hence, by the Jensen-Yui criterion, $\text{Gal}(f_t(x)) \simeq D_7$. □

THEOREM 4.6. (i) *There exist infinitely many integers t satisfying*

$$\begin{aligned} 2 \parallel t, \quad t \equiv 1 \pmod{3}, \quad t \equiv 1, 2 \text{ or } 4 \pmod{5}, \\ 7t^3 + 35t^2 + 21t + 1 \text{ is square-free} > 1, \end{aligned} \tag{4.13}$$

and for these values of t ,

$$i(L) = 2^4. \tag{4.14}$$

(ii) *There exist infinitely many integers t satisfying*

$$\begin{aligned} 2 \parallel t, \quad 3 \parallel t, \quad t \equiv 1, 2 \text{ or } 4 \pmod{5}, \\ 7t^3 + 35t^2 + 21t + 1 \text{ is square-free} > 1. \end{aligned} \tag{4.15}$$

and for these values of t ,

$$i(L) = 2^4 3. \tag{4.16}$$

Proof. The infinitude of integers of the required forms follows from a result of Erdős [9].

Under conditions (4.13) and (4.15), L is a dihedral field of degree 7, by Lemma 4.5. With the notation of Theorem 1.1, we see from (4.2) that $K = \mathbb{Q}(\sqrt{t})$. Clearly $2 \mid d(K)$. By Theorem 1.1, 2 is a common index divisor of L . Also from Theorem 1.1, we see that $2 = R_1 R_2^2 R_3^2 R_4^2$ for distinct prime ideals R_1, R_2, R_3, R_4 of L . Hence, by Engstrom [5, Table, page 235], we see that $2^4 \parallel i(L)$. For both (4.13) and (4.15) we have by Lemma 4.1(ii) $5 \nmid D(f_t)$

so $5 \nmid i(L)$. For (4.13) by Lemma 4.1(i) we have $3 \nmid D(f_i)$, so $3 \nmid i(L)$. As $[L : \mathbb{Q}] = 7$, by [5, page 224], the only possible prime divisors of $i(L)$ are 2, 3, and 5. Hence $i(L) = 2^4$ in case (i). For case (ii), by Theorem 1.1, 3 is a common index divisor of L . Also, by Theorem 1.1, we see that $3 = R_1 R_2^2 R_3^2 R_4^2$ for distinct prime ideals R_1, R_2, R_3, R_4 of L . Hence, by Engstrom [5, Table, page 235], we see that $3 \parallel i(L)$. Finally, as the only possible prime divisors of $i(L)$ are 2, 3, and 5, we deduce that $i(L) = 2^4 3$ in case (ii). \square

5. A dihedral field of degree 11

Let

$$\begin{aligned} f(x) = & x^{11} - 2x^{10} - 51x^9 - x^8 + 536x^7 \\ & + 3x^6 - 1999x^5 + 281x^4 + 2571x^3 \\ & - 485x^2 - 680x + 69. \end{aligned} \quad (5.1)$$

By MAPLE, $f(x)$ is irreducible over \mathbb{Q} . Let θ be a root of $f(x)$ and set $L = \mathbb{Q}(\theta)$, so that $[L : \mathbb{Q}] = 11$. Let M be the splitting field of $f(x)$. It is known that M is the Hilbert class field of $K = \mathbb{Q}(\sqrt{10401})$ [10] so that L is a dihedral extension of \mathbb{Q} . By Theorem 1.1, 3 is a common index divisor of L , hence L is not monogenic.

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