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DEFINING EQUATIONS OF $X_1(2N)$

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Abstract. In this paper, we give a new method to get defining equations of modular curves $X_1(2N)$ which show the moduli problems.

1. Introduction

For a positive integer N, consider the congruence subgroup $\Gamma_1(N)$ of $\mathrm{SL}_2(\mathbb{Z})$ defined by

$$\Gamma_1(N) := \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{SL}_2(\mathbb{Z}) \mid \begin{pmatrix} a & b \\ c & d \end{pmatrix} \equiv \begin{pmatrix} 1 & * \\ 0 & 1 \end{pmatrix} \bmod N \right\}.$$

Then the modular curve $X_1(N)$ corresponding to $\Gamma_1(N)$ is related to moduli problems of elliptic curves with N-torsion points. Defining equations of a modular curve are any polynomials that yield an isomorphic function field of that modular curve(cf. [6]).

Baaziz [1], Ishida and Ishii [3], Reichert [5], and Yang [6] suggested some methods to find defining equations of $X_1(N)$. The purpose of this paper is to present a new method for obtaining equations of $X_1(N)$ for even integers N. The author, Kim and Lee [4] found defining equations

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of $X_1(20)$ and $X_1(24)$ whose degree in one of variables is 4 for obtaining infinitely many points over quartic number fields. We improve the method in [4] to get defining equations of $X_1(2N)$ for all N.

2. Preliminaries

The Tate normal form of an elliptic curve with $P = (0,0)$ is given as follows:

$$E(b,c) : y^2 + (1-c)xy - by = x^3 - bx^2,$$

and this is nonsingular if and only if $b \neq 0$. In this case, P is not of order 2 or 3(cf. [2]). On the curve $E(b,c)$ we have the following by the chord-tangent method(cf. [5]):

$$\begin{aligned}
P &= (0,\ 0),\\
2P &= (b,\ bc),\\
3P &= (c,\ b-c),\\
4P &= \big(r(r-1),\ r^2(c-r+1)\big)\,;\quad b = cr,\\
5P &= \big(rs(s-1),\ rs^2(r-s)\big)\,;\quad c = s(r-1),\\
6P &= \left(\frac{s(r-1)(r-s)}{(s-1)^2},\ \frac{s^2(r-1)^2(rs-2r+1)}{(s-1)^3}\right).
\end{aligned} \tag{1}$$

The condition $NP = O$ in $E(b,c)$ gives a defining equation for $X_1(N)$. For example, $11P = O$ implies $5P = -6P$, so

$$x_{5P} = x_{-6P} = x_{6P},$$

where x_{nP} denote the x-coordinate of the n-multiple nP of P. Eq. (1) implies that

$$rs(s-1) = \frac{s(r-1)(r-s)}{(s-1)^2}. \tag{2}$$

Without loss of generality, the cases $s = 0$ and $s = 1$ may be excluded. Then Eq. (2) becomes as follows:

$$-rs^3 + 3rs^2 - 4rs + r^2 + s = 0,$$

which is one of the equations of $X_1(11)$, called the *raw form* of $X_1(11)$. By the coordinate changes $s = v/u+1$ and $r = v+1$, we get the following equation:

$$v^2 + v = u^3 - u^2.$$

3. Defining equations of $X_1(2N)$

Let E be an elliptic curve with a N-torsion point P. Suppose Q is a point of E with $2Q = P$ and $Q \notin \langle P \rangle$. Then Q is a $2N$-torsion point of E. The set of pairs (E, P) defines $X_1(N)$, and so the set of pairs (E, Q) does $X_1(2N)$. Thus it suffices to find a method to parametrize the pairs (E, Q) for getting a defining equation of $X_1(2N)$.

Suppose E is an elliptic curve defined by

$$E : y^2 + (1-c)xy - by = x^3 - bx^2,$$

and $P = (0,0)$ is an N-torsion point of E. By the coordinate changes $x \to x$ and $y \to y + \frac{c-1}{2}x + \frac{b}{2}$, E is changed to the following:

$$E' : \; y^2 = x^3 + \frac{(c-1)^2 - 4b}{4}x^2 + \frac{b(c-1)}{2}x + \frac{b^2}{4}.$$

For simplicity, we write E' by

$$y^2 = x^3 + Ax^2 + Bx + C,$$

where $A = \frac{(c-1)^2-4b}{4}, B = \frac{b(c-1)}{2}$, and $C = \frac{b^2}{4}$. Then $(0, -\frac{b}{2})$ is an N-torsion point of the curve E'.

Now consider a point $Q = (x_1, y_1)$ with $2Q = (0, -\frac{b}{2})$. Take $y = mx + \frac{b}{2}$ as the line through $(0, \frac{b}{2})$ tangent at the unknown point Q. Then the three roots of

$$x^3 + Ax^2 + Bx + C - \left(mx + \frac{b}{2}\right)^2 \tag{3}$$

are $0, x_1$ and x_1, i.e., x_1 is a double root of Eq. (3). Thus

$$\frac{x^3 + Ax^2 + Bx + C - (mx + \frac{b}{2})^2}{x} = (x - x_1)^2,$$

and hence the discriminant of

$$x^2 + (A - m^2)x + (B - bm) \tag{4}$$

is equal to 0, i.e., m satisfies the following quartic equation:

$$(z^2 - A)^2 + 4(bz - B) = 0. \tag{5}$$

Suppose m_0 is a root of Eq. (5). Then

$$x_1 = \frac{m_0^2 - A}{2}$$

is a double root of Eq. (4) and hence also of Eq. (3). Thus $2(x_1, m_0x_1 + \frac{b}{2}) = (0, -\frac{b}{2})$. In other words, $Q = (x_1, y_1)$ is a $2N$-torsion point of E' where $y_1 = m_0x_1 + \frac{b}{2}$.

Now suppose $f_N(u, v) = 0$ is a defining eqution of $X_1(N)$. Then each common root of $f_N(u, v) = 0$ and Eq. (5) is corresponding to a pair of (E', Q) where Q is a $2N$-torsion point of an elliptic curve E'. Therefore we have the following result

THEOREM 3.1. *A defining equation of the modular curve $X_1(2N)$ is given by*

$$\begin{cases} f_N(u, v) = 0, \\ (z^2 - A)^2 + 4(bz - B) = 0, \end{cases}$$

where $f_N(u, v) = 0$ is a defining eqution of $X_1(N)$ and b, A, B are defined as above.

EXAMPLE 3.2. *A defining equation of $X_1(11)$ is*

$$v^2 + v = u^3 - u^2,$$

and

$$b = \frac{v(v+1)(v+u)}{u}, \quad c = \frac{v(v+u)}{u}.$$

Therefore a defining equation of $X_1(22)$ is given by the following:

$$X_1(22) : \begin{cases} v^2 + v = u^3 - u^2, \\ 16u^4z^4 - 8u^2(v^4 - 2uv^3 - 3(u^2 + 2u)v^2 - 6u^2v + u^2)z^2 \\ +64u^3v(v+1)(v+u)z + v^8 - 4uv^7 - 2u(u+6)v^6 \\ +4(3u-5)u^2v^5 + u^2(9u^2 - 4u + 6)v^4 + 4(u+9)u^3v^3 \\ +10(3u+2)u^3v^2 + 20u^4v + u^4 = 0. \end{cases}$$

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