ON THE ORDERS OF AUTOMORPHISMS OF A CLOSED Riemann Surface

Kenji Nakagawa
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OF A CLOSED RIEMANN SURFACE

KENJI NAKAGAWA

Let $S$ be a closed Riemann surface of genus $g$ ($\geq 2$). It is known that the maximum value of the orders of automorphisms of $S$ is $4g + 2$. In this paper we determine the orders of automorphisms of $S$ which are greater than or equal to $3g$, and characterize those Riemann surfaces having the corresponding automorphisms. Except for several cases, such Riemann surfaces are determined uniquely up to conformal equivalence.

**Theorem 1.** Let $N(S, h)$ be the order of an automorphism $h$ of $S$. Then,

$$\max_{S, h} N(S, h) = 4g + 2.$$  

The Riemann surface having the automorphism of maximum order $4g + 2$ is conformally equivalent to the Riemann surface defined by

$$y^2 = x(x^{2g+1} - 1).$$

The automorphism $h$ of order $4g + 2$ is given by

$$h(x, y) = (e^{2\pi i/(2g+1)}x, e^{2\pi i/(4g+2)}y).$$

Although the existence of the Riemann surface with the automorphism of order $4g + 2$ is well known, in the above theorem the uniqueness (up to conformal equivalence) is shown.

To simplify, we write Theorem 1 in the following form:

$$\max_N N = 4g + 2, \quad S: y^2 = x(x^{2g+1} - 1),$$

$$h(x, y) = (e^{2\pi i/(2g+1)}x, e^{2\pi i/(4g+2)}y).$$

Under similar notation,

**Theorem 2.**

$$\max_{N < 4g+2} N = 4g, \quad S: y^2 = x(x^{2g} - 1), \quad h(x, y) = (e^{2\pi i/2gx}, e^{2\pi i/4gy}).$$

**Theorem 3.** If $g \equiv 0 \pmod{3}$, for $g \neq 3$,

$$\max_{N < 4g} N = 3g + 3, \quad S: y^3 = x^2(x^{g+1} - 1),$$

$$h(x, y) = (e^{2\pi i/(g+1)}x, e^{4\pi i/(3g+3)}y).$$
For $g = 3$, we have $4g = 3g + 3$. Then there exist two Riemann surfaces defined by
\[
y^2 = x(x^6 - 1) \quad \text{and} \quad y^3 = x^2(x^4 - 1)
\]
which have an automorphism of order 12. Furthermore,
\[
\max_{N < 3g + 3} N = 3g, \quad S: y^3 = x(x^g - 1), \quad h(x, y) = (e^{2\pi i/g}x, e^{2\pi i/3g}y),
\]
except for
\[
S: y^{20} = x^5(x - 1)^4 \quad (g = 6, N = 20 = 3g + 2),
\]
\[
: y^{28} = x^7(x - 1)^4 \quad (g = 9, N = 28 = 3g + 1),
\]
\[
: y^{36} = x^9(x - 1)^4 \quad (g = 12, N = 36 = 3g).
\]

**Theorem 4.** If $g \equiv 1 \pmod{3}$,
\[
\max_{N < 3g + 3} N = 3g + 3, \quad S: y^3 = x(x^{g+1} - 1),
\]
\[
h(x, y) = (e^{2\pi i/(g+1)}x, e^{2\pi i/(3g+3)}y).
\]

\[
\max_{N < 3g + 3} N = 3g, \quad S: y^3 = x(x^g - 1), \quad h(x, y) = (e^{2\pi i/g}x, e^{2\pi i/3g}y),
\]
except for
\[
S: y^{12} = x^3(x - 1)^2 \quad (g = 4, N = 12 = 3g),
\]
\[
: y^{30} = x^5(x - 1)^6 \quad (g = 10, N = 30 = 3g).
\]

**Theorem 5.** If $g \equiv 2 \pmod{3}$,
\[
\max_{N < 4g} N = 3g, \quad S: y^3 = x^2(x^g - 1), \quad h(x, y) = (e^{2\pi i/g}x, e^{4\pi i/3g}y),
\]
except for
\[
S: y^6 = x^3(x - 1)^3(x - \xi)^2 \quad (g = 2, N = 6 = 3g, \xi \in \mathbb{C}, \xi \neq 0, 1).
\]

We introduce the following notation; $\langle h \rangle$ denotes the cyclic group generated by $h$ of order $N$. $\tilde{S} = S/\langle h \rangle$ denotes the closed Riemann surface of genus $\tilde{g}$ obtained by identifying those points on $S$ which are equivalent under the action of $\langle h \rangle$ on $S$. $\tilde{p}_1, \ldots, \tilde{p}_t \in \tilde{S}$ denote the projections of branch points of the covering map $\varphi: S \to \tilde{S}$. $v_1, \ldots, v_t$ denote the multiplicities of $\varphi$ at the branch points over $\tilde{p}_1, \ldots, \tilde{p}_t$, respectively.
A Fuchsian group is said to be a \((\gamma; m_1, \ldots, m_n)\) group if its signature is \((\gamma; m_1, \ldots, m_n)\). If \(n = 0\), it is said to be a surface group. A homomorphism from a Fuchsian group onto a finite group is said to be a surface kernel homomorphism if its kernel is a surface group.

**Lemma 1.** (Harvey [2].) Let \(\Gamma\) be a \((\gamma; m_1, \ldots, m_n)\) group, \(Z_N\) the cyclic group of order \(N\), and \(M = \text{lcm}(m_1, \ldots, m_n)\). Then there exists a surface kernel homomorphism from \(\Gamma\) onto \(Z_N\) if and only if the signature \((\gamma; m_1, \ldots, m_n)\) satisfies the following l.c.m. condition;

1. \(M = \text{lcm}(m_1, \ldots, m_i, \ldots, m_n)\) \((i = 1, \ldots, n)\). Here, \(m_i\) denotes the omission of \(m_i\).
2. \(M \mid N\), if \(\gamma = 0\) then \(M = N\).
3. \(n \neq 1\), if \(\gamma = 0\) then \(n \geq 3\).
4. If \(2 \mid M\), the number of \(m_i\)'s which are divisible by the maximum power of 2 which divides \(M\) is even.

**Lemma 2.** (Riemann-Hurwitz relation.)

\[
2g - 2 = N(2\bar{g} - 2) + N \sum_{i=1}^{t} \left(1 - \frac{1}{v_i}\right).
\]

**Lemma 3.** If \(\bar{t} = 0\), then \(S\) is conformally equivalent to the Riemann surface defined by

\[
y^N = f(x) \quad (f(x) \text{ is a polynomial of } x).
\]

**Lemma 4.** \((\bar{g}; v_1, \ldots, v_t)\) satisfies the l.c.m. condition.

**Proof.** Let \(D\) be the unit disk, \(K\) a Fuchsian surface group which uniformize \(S\), and \(\psi\) the natural projection from \(D\) onto \(S = D/K\). Let \(D^* = D - (\varphi \circ \psi)^{-1}\{\bar{p}_1, \ldots, \bar{p}_t\}\), \(\tilde{S}^* = \tilde{S} - \{\tilde{p}_1, \ldots, \tilde{p}_t\}\), and let \(\Gamma\) be the covering transformation group of the covering \(\varphi \circ \psi: D^* \rightarrow S^*\). Then \(\Gamma\) is a \((\bar{g}; v_1, \ldots, v_t)\) group and \(\Gamma/K = Z_N\). So from Lemma 1, we find that \((\bar{g}; v_1, \ldots, v_t)\) satisfies the l.c.m. condition.

**Lemma 5.** If \(N > 2g - 2\), then \(\bar{g} = 0\), \(t = 3, 4\).

**Proof.** From the Riemann-Hurwitz relation, if \(\bar{g} \geq 2\),

\[
2g - 2 \geq N(2\bar{g} - 2) \geq 2N.
\]

This contradicts the hypothesis. If \(\bar{g} = 1\), from the l.c.m. condition, \(t \geq 2\).
Then,
\[ 2g - 2 = N \sum_{i=1}^{t} \left( 1 - \frac{1}{v_i} \right) \geq tN/2 \geq N. \]
This also contradicts the hypothesis. So \( \tilde{g} = 0 \), and
\[ 2g - 2 = -2N + N \sum_{i=1}^{t} \left( 1 - \frac{1}{v_i} \right) \geq \frac{(t - 4)N}{2}. \]
Thus \( t = 3, 4 \) or 5. But if \( t = 5 \),
\[ 2g - 2 = N \left( 3 - \sum_{i=1}^{5} \frac{1}{v_i} \right), \]
and from \( N > 2g - 2 \), we find that
\[ 2 < \sum_{i=1}^{5} \frac{1}{v_i} < 3. \]
The signatures which satisfy these inequalities are the following:
\[ (0; 2, 2, 2, 2, \ast), \ (0; 2, 2, 2, 3, 3), \ (0; 2, 2, 2, 3, 4), \ (0; 2, 2, 2, 3, 5). \]
None of these satisfies the l.c.m. condition.

**Lemma 6.** If \( N > 2g + 2 \), then \( t = 3 \).

*Proof.* From Lemma 5, \( \tilde{g} = 0 \), \( t = 3, 4 \). If \( t = 4 \), from the Riemann-Hurwitz relation, we find that
\[ 1 < \sum_{i=1}^{4} \frac{1}{v_i} < 2. \]
The signatures which satisfy these inequalities and the l.c.m. condition are the following (\( N \) on the right side is given by \( N = M = \text{lcm}(v_1, v_2, v_3, v_4) \), \( g \) is calculated from \( \tilde{g}, v_1, v_2, v_3, v_4, N \) by the Riemann-Hurwitz relation):
\[ (0; 2, 2, m, m) \ (m \neq 2) \quad \text{if} \ 2|m, \quad g = m/2, \ N = m = 2g, \]
\[ \quad \text{if} \ 2 \nmid m, \quad g = m - 1, \ N = 2m = 2g + 2, \]
\[ (0; 2, 3, 3, 6) \quad g = 3, \ N = 6 = 2g, \]
\[ (0; 2, 3, 4, 12) \quad g = 6, \ N = 12 = 2g, \]
\[ (0; 2, 3, 5, 30) \quad g = 15, \ N = 30 = 2g, \]
\[ (0; 3, 3, 3, 3) \quad g = 2, \ N = 3 = 2g - 1, \]
\[ (0; 3, 3, 4, 4) \quad g = 6, \ N = 12 = 2g, \]
\[ (0; 3, 3, 5, 5) \quad g = 8, \ N = 15 = 2g - 1. \]
None of these satisfies \( N > 2g + 2 \).
Proof of theorems. If we assume $N \geq 3g$ ($\geq 2g + 2$), from Lemma 3, $\tilde{g} = 0$, $t = 3$ or exceptionally (I) $\tilde{g} = 0$, $t = 4$, $(\tilde{g}; v_1, v_2, v_3, v_4) = (0; 2, 2, 3, 3)$, $g = 2$, $N = 6$. When $\tilde{g} = 0$, $t = 3$, from the Riemann-Hurwitz relation, we find that

$$\frac{1}{3} \leq \frac{1}{v_1} + \frac{1}{v_2} + \frac{1}{v_3} < 1.$$  

The signatures which satisfy these inequalities and the l.c.m. condition are the following;

<table>
<thead>
<tr>
<th>Signature</th>
<th>$N$</th>
<th>$\tilde{g}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(0; 2, m, m)$ (2</td>
<td>m then 4</td>
<td>m ($m \neq 4$))</td>
</tr>
<tr>
<td>$(0; 2, m, 2m)$ (2 + m ($m \neq 3$))</td>
<td>$g = (m - 1)/2$, $N = 2m = 4g + 2$,</td>
<td></td>
</tr>
<tr>
<td>$(0; 3, m, m)$ (3</td>
<td>m ($m \neq 3$))</td>
<td>$g = m/3$, $N = m = 3g$,</td>
</tr>
<tr>
<td>$(0; 3, m, 3m)$ (3 + m)</td>
<td>$g = m - 1$, $N = 3m = 3g + 3$,</td>
<td></td>
</tr>
<tr>
<td>(II) $(0; 4, 5, 20)$</td>
<td>$g = 6$, $N = 20 = 3g + 2$,</td>
<td></td>
</tr>
<tr>
<td>$(0; 4, 6, 12)$</td>
<td>$g = 4$, $N = 12 = 3g$,</td>
<td></td>
</tr>
<tr>
<td>$(0; 4, 7, 28)$</td>
<td>$g = 9$, $N = 28 = 3g + 1$,</td>
<td></td>
</tr>
<tr>
<td>$(0; 4, 9, 36)$</td>
<td>$g = 12$, $N = 36 = 3g$,</td>
<td></td>
</tr>
<tr>
<td>$(0; 5, 6, 30)$</td>
<td>$g = 10$, $N = 30 = 3g$.</td>
<td></td>
</tr>
</tbody>
</table>

So if we exclude the exceptional cases (I) and (II), the signatures $(\tilde{g}; v_1, v_2, v_3)$ are listed as following;

If $N = 4g + 2$, $(0; 2, 2g + 1, 4g + 2)$.
If $N = 4g$, $(0; 2, 4g, 4g)$.
If $N = 3g + 3$, $(0; 3, g + 1, 3g + 3)$.
(In this case, $3 + m$ and $g = m - 1$ imply $g \equiv 0, 1$ (mod 3).)
If $N = 3g$, $(0; 3, 3g, 3g)$.

Now $S$ branches over three points of the Riemann sphere $\overline{C}$, and the branching orders are given as above, so if we assume that the projections of branch points are 0, 1 and $\infty$, from Lemma 3, $S$ is conformally equivalent to the Riemann surface defined by

$$y^N = x^a(x - 1)^b,$$

where $a, b$ are given by the following conditions;

$$1 \leq a, b < N, \quad N/(N, a) = v_1, \quad N/(N, b) = v_2, \quad N/(N, a + b) = v_3.$$  

($N, a$) denotes the g.c.m. of $N$ and $a$.

Then if $N = 4g + 2$, $S$ is defined by

$$y^{4g + 2} = x^{2g + 1}(x - 1)^{2k} \quad ((2g + 1, k) = 1, 1 \leq k < 2g + 1).$$
This surface is conformally equivalent to the Riemann surface defined by
\[ Y^2 = X(X^{2g+1} - 1) \]
under the birational transformation

\[
\begin{align*}
  y &= \frac{Y}{X^{g+1+k}}, \\
  x &= -\frac{1}{X^{2g+1}} + 1,
\end{align*}
\]

where \((a, b, c), (p, q, r)\) are the solutions of the indeterminate equations
\[
\begin{align*}
  2a + (2g + 1)c &= 1, \\
  b + kc &= 0, \\
  p + r &= 0, \\
  (2g + 1)q + 2kr &= 1.
\end{align*}
\]

If \(N = 4g\), \(S\) is defined by
\[(2) \quad y^{4g} = x^{2g}(x - 1)^k \quad ((4g, k) = (4g, 2g - k) = 1, 1 \leq k < 4g).\]

This surface is conformally equivalent to the Riemann surface defined by
\[ Y^2 = X(X^{2g} - 1), \]
under the birational transformation

\[
\begin{align*}
  y &= e^{\pi i/(2g+1)}X^{(k-1)/2}Y, \\
  x &= -X^{2g} + 1,
\end{align*}
\]

where \((a, b, c), (p, q, r)\) are the solutions of the indeterminate equations
\[
\begin{align*}
  2a + c &= 1, \\
  4gb + kc &= 1, \\
  2gq + kr &= 1.
\end{align*}
\]

If \(N = 3g + 3\), \(S\) is defined by
\[(3) \quad y^{3g+3} = x^{j(3g+1)}(x - 1)^3k \quad ((g + 1, k) = (3g + 3, (3 - j)(g + 1) - 3k) = 1, \\
\quad j = 1, 2, 1 \leq k < g + 1).\]

When \(g \equiv 0 \pmod{3}\), \(3\) is conformally equivalent to the Riemann surface defined by
\[ Y^3 = X^2(X^{g+1} - 1), \]
under the birational transformation

\[
\begin{align*}
&y = e^{k\pi i/(g+1)} \frac{Y^j}{X^{k+j(g/3+1)}}, \\
x = -\frac{1}{X^{g+1}} + 1,
\end{align*}
\]

\[
\begin{align*}
Y &= e^{(g+3)\pi i/(3g+3)} \frac{x^a(x-1)^b y^{(g+1)c}}{(x^p(x-1)^q y^{3r})^{g/3+1}}, \\
X &= e^{\pi i/(g+1)} \frac{1}{x^p(x-1)^q y^{3r}},
\end{align*}
\]

where \((a, b, c), (p, q, r)\) are the solutions of the indeterminate equations

\[
\begin{align*}
3a + j(g + 1)c &= 1, & p + jr &= 0, \\
b + kc &= 0, & (g + 1)q + 3kr &= 1.
\end{align*}
\]

When \(g \equiv 1 \pmod{3}\), (3) is conformally equivalent to the Riemann surface defined by

\[
Y^3 = X(X^{g+1} - 1),
\]

under the birational transformation

\[
\begin{align*}
&y = e^{k\pi i/(g+1)} \frac{Y^j}{X^{k+j(g/2)/3}}, \\
x = -\frac{1}{X^{g+1}} + 1,
\end{align*}
\]

\[
\begin{align*}
Y &= e^{(g+2)\pi i/(3g+3)} \frac{x^a(x-1)^b y^{(g+1)c}}{(x^p(x-1)^q y^{3r})^{(g+2)/3}}, \\
X &= e^{\pi i/(g+1)} \frac{1}{x^p(x-1)^q y^{3r}},
\end{align*}
\]

where \((a, b, c), (p, q, r)\) are the solutions of the indeterminate equations

\[
\begin{align*}
3a + j(g + 1)c &= 1, & p + jr &= 0, \\
b + kc &= 0, & gp + kr &= 1.
\end{align*}
\]

If \(N = 3g\), \(S\) is defined by

\[
y^{3g} = x^j g(x - 1)^k
\]

\[
((3g, k) = (3g, (3 - j)g - k) = 1, j = 1, 2, 1 \leq k < g).
\]
Then we notice that \( k \equiv j \pmod{3} \) or \( k \equiv 2j \pmod{3} \). In the case \( k \equiv j \pmod{3} \), (4) is conformally equivalent to the Riemann surface defined by

\[
Y^3 = X(X^g - 1),
\]

under the birational transformation

\[
\begin{align*}
\begin{cases}
    y = e^{((k+j)\pi i/3g)}X^{(k-j)/3}Y, \\
x = -X^g + 1,
\end{cases}
\quad
\begin{cases}
    Y = e^{((g+1)\pi i/3g)}x^a(x - 1)^b y^c, \\
    X = e^{\pi i/g}x^p(x - 1)^q y^{3r},
\end{cases}
\end{align*}
\]

where \((a, b, c), (p, q, r)\) are the solutions of the indeterminate equations

\[
\begin{align*}
\begin{cases}
    3a + jc = 1, \\
    3gb + kc = 1,
\end{cases}
\quad
\begin{cases}
    p + jr = 0, \\
    gq + kr = 1.
\end{cases}
\end{align*}
\]

In the case \( k \equiv 2j \pmod{3} \), (4) is conformally equivalent to the Riemann surface defined by

\[
Y^3 = X^2(X^g - 1),
\]

under the birational transformation

\[
\begin{align*}
\begin{cases}
    y = e^{((k+jg)\pi i/3g)}X^{(k-2j)/3}Y, \\
x = -X^g + 1,
\end{cases}
\quad
\begin{cases}
    Y = e^{\pi i/3}x^a(x - 1)^b y^c, \\
    X = e^{\pi i/3}x^p(x - 1)^q y^{3r},
\end{cases}
\end{align*}
\]

where \((a, b, c), (p, q, r)\) are the solutions of the indeterminate equations

\[
\begin{align*}
\begin{cases}
    3a + jc = 1, \\
    3gb + kc = 2,
\end{cases}
\quad
\begin{cases}
    p + jr = 0, \\
    gq + kr = 1.
\end{cases}
\end{align*}
\]

Finally, if \( g \equiv 0 \pmod{3} \), two Riemann surfaces

\[
y^3 = x(x^g - 1) \quad \text{and} \quad Y^3 = X^2(X^g - 1)
\]

are conformally equivalent under the birational transformation

\[
\begin{align*}
\begin{cases}
    y = -X^{g/3+1}Y, \\
x = X^{-1},
\end{cases}
\quad
\begin{cases}
    Y = -x^{g/3+1}y, \\
    X = x^{-1}.
\end{cases}
\end{align*}
\]

For a surface in (4), if \( g \equiv 1 \pmod{3} \), we obtain \( k \equiv j \pmod{3} \), while if \( g \equiv 2 \pmod{3} \), \( k \equiv 2j \pmod{3} \).

In the exceptional case (I), the surfaces are conformally equivalent to the Riemann surface defined by

\[
y^6 = x^3(x - 1)^3(x - \xi)^2 \quad (\xi \in \mathbb{C}, \xi \neq 0, 1).
\]

In the case (II), the surfaces which have the same signature are conformally equivalent to each other. Thus we have the following forms
of $S$:

\[
\begin{align*}
y^{20} &= x^5(x - 1)^4, \\
y^{28} &= x^7(x - 1)^4, \\
y^{12} &= x^3(x - 1)^2, \\
y^{36} &= x^9(x - 1)^4, \\
y^{30} &= x^6(x - 1)^5,
\end{align*}
\]

(0; 4, 5, 20), (0; 4, 7, 28), (0; 4, 6, 12), (0; 4, 9, 36), (0; 5, 6, 30).

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