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ALGEBRAIC INDEPENDENCE RESULTS RELATED TO LINEAR RECURRENCES

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1. Introduction and results

One of the techniques used to prove the algebraic independence of numbers is Mahler's method, which deals with the values of so-called Mahler functions satisfying a certain type of functional equation. In order to apply the method, one must confirm the algebraic independence of the Mahler functions themselves. This can be reduced, in many cases, to their linear independence modulo the rational function field, that is, the problem of determining whether a nonzero linear combination of them is a rational function or not. In the case of one variable, this can be treated by arguments involving poles of rational functions. However, in the case of several variables, this method is not available. In this paper we shall overcome this difficulty by considering a generic point of an irreducible algebraic variety. Theorems 1 and 2 in this paper assert that certain types of functional equations in several variables have no nontrivial rational function solutions. As applications, we shall prove the algebraic independence of various kinds of reciprocal sums of linear recurrences in Theorems 3 and 4, and that of the values at algebraic numbers of power series, Lambert series, and infinite products generated by linear recurrences in Theorem 5.

Let $\Omega = (\omega_{ij})$ be an $n \times n$ matrix with nonnegative integer entries. If $z = (z_1, \dots, z_n)$ is a point of C^n with C the set of complex numbers, we define a transformation $\Omega : C^n \rightarrow C^n$ by

$$(1) \quad \Omega z = \left(\prod_{j=1}^n z_j^{\omega_{1j}}, \dots, \prod_{j=1}^n z_j^{\omega_{nj}} \right).$$

Let $\{a_k\}_{k \geq 0}$ be a linear recurrence of nonnegative integers satisfying

$$(2) \quad a_{k+n} = c_1 a_{k+n-1} + \dots + c_n a_k \quad (k = 0, 1, 2, \dots),$$

where a_0, \dots, a_{n-1} are not all zero and c_1, \dots, c_n are nonnegative integers with $c_n \neq 0$. We define a polynomial associated with (2) by

$$(3) \quad \Phi(X) = X^n - c_1 X^{n-1} - \dots - c_n.$$

Our results assume that $\Phi(\pm 1) \neq 0$ and the ratio of any pair of distinct roots of $\Phi(X)$ is not a root of unity and that $\{a_k\}_{k \geq 0}$ is not a geometric progression. We define a monomial

$$(4) \quad P(\mathbf{z}) = z_1^{a_{n-1}} \cdots z_n^{a_0},$$

which is denoted similarly to (1) by

$$(5) \quad P(\mathbf{z}) = (a_{n-1}, \dots, a_0)\mathbf{z}.$$

Let

$$(6) \quad \Omega = \begin{pmatrix} c_1 & 1 & 0 & \cdots & 0 \\ c_2 & 0 & 1 & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & 0 \\ \vdots & \vdots & & \ddots & 1 \\ c_n & 0 & \cdots & \cdots & 0 \end{pmatrix}.$$

It follows from (1), (2), and (5) that

$$P(\Omega^k \mathbf{z}) = z_1^{a_{k+n-1}} \cdots z_n^{a_k} \quad (k \geq 0).$$

In what follows, C and \overline{C} denote a field of characteristic 0 and its algebraic closure, respectively. Let $F(z_1, \dots, z_n)$ and $F[[z_1, \dots, z_n]]$ denote the field of rational functions and the ring of formal power series in variables z_1, \dots, z_n with coefficients in a field F , respectively, and F^\times the multiplicative group of nonzero elements of F . The following are the main theorems of the present paper.

Theorem 1. *Suppose that $G(\mathbf{z}) \in \overline{C}[[z_1, \dots, z_n]]$ satisfies the functional equation of the form*

$$(7) \quad G(\mathbf{z}) = \alpha G(\Omega^p \mathbf{z}) + \sum_{k=q}^{p+q-1} Q_k(P(\Omega^k \mathbf{z})),$$

where $\alpha \neq 0$ is an element of \overline{C} , Ω is defined by (6), $p > 0$, $q \geq 0$ are integers, and $Q_k(X) \in \overline{C}(X)$ ($q \leq k \leq p+q-1$) are defined at $X=0$. If $G(\mathbf{z}) \in \overline{C}(z_1, \dots, z_n)$, then $G(\mathbf{z}) \in \overline{C}$ and $Q_k(X) \in \overline{C}$ ($q \leq k \leq p+q-1$).

Theorem 2. *Suppose that $G(\mathbf{z})$ is an element of the quotient field of $\overline{C}[[z_1, \dots, z_n]]$ satisfying the functional equation of the form*

$$(8) \quad G(\mathbf{z}) = \left(\prod_{k=q}^{p+q-1} Q_k(P(\Omega^k \mathbf{z})) \right) G(\Omega^p \mathbf{z}),$$

where Ω , p , q , and $Q_k(X)$ are as in Theorem 1. Assume that $Q_k(0) \neq 0$. If $G(z) \in \overline{C}(z_1, \dots, z_n)$, then $G(z) \in \overline{C}$ and $Q_k(X) \in \overline{C}^\times$ ($q \leq k \leq p + q - 1$).

First we shall state our results on algebraic independence of reciprocal sums of linear recurrences, Theorems 3 and 4, obtained as applications of Theorem 1. We prepare some notations.

Let $\{R_k\}_{k \geq 0}$ be a linear recurrence expressed as

$$(9) \quad R_k = b_1 \rho_1^k + \dots + b_r \rho_r^k \quad (k \geq 0),$$

where b_1, \dots, b_r are nonzero algebraic numbers and ρ_1, \dots, ρ_r are nonzero distinct algebraic numbers satisfying

$$(10) \quad |\rho_1| > \max\{1, |\rho_2|, \dots, |\rho_r|\}.$$

Typical examples of such $\{R_k\}_{k \geq 0}$ are the Fibonacci numbers $\{F_k\}_{k \geq 0}$ defined by

$$F_0 = 0, \quad F_1 = 1, \quad F_{k+2} = F_{k+1} + F_k \quad (k \geq 0)$$

and the Lucas numbers $\{L_k\}_{k \geq 0}$ defined by

$$L_0 = 2, \quad L_1 = 1, \quad L_{k+2} = L_{k+1} + L_k \quad (k \geq 0),$$

since

$$F_k = \frac{1}{\sqrt{5}} \left(\left(\frac{1 + \sqrt{5}}{2} \right)^k - \left(\frac{1 - \sqrt{5}}{2} \right)^k \right) \quad (k \geq 0)$$

and

$$L_k = \left(\frac{1 + \sqrt{5}}{2} \right)^k + \left(\frac{1 - \sqrt{5}}{2} \right)^k \quad (k \geq 0).$$

We shall prove the algebraic independence of reciprocal sums of linear recurrences such as

$$(11) \quad \sum'_{k \geq 0} \frac{b_k}{(R_{a_k+h})^m},$$

where $\{b_k\}_{k \geq 0}$ is a linear recurrence of algebraic numbers not identically zero, $\{a_k\}_{k \geq 0}$ is as above, and $m \geq 1$, h are integers. Here and in what follows, the sum $\sum'_{k \geq 0}$ is taken over those k which satisfy $a_k + h \geq 0$ and $R_{a_k+h} \neq 0$. For example,

the algebraic independence of the numbers

$$\sum'_{k \geq 0} \frac{1}{(F_{F_k+h})^m} \quad (h \in \mathbf{Z}, m \in \mathbf{N})$$

can be deduced from Theorem 4 below. Here \mathbf{Z} and \mathbf{N} denote the sets of rational and positive integers, respectively.

It is interesting to compare our results to those obtained by various authors in the case where $\{a_k\}_{k \geq 0}$ is a geometric progression. Lucas [7] showed that

$$\sum_{k \geq 0} \frac{1}{F_{2^k}} = \frac{7 - \sqrt{5}}{2}.$$

Let $\{p_k\}_{k \geq 0}$ be a periodic sequence of algebraic numbers not identically zero. Bundschuh and Pethö [1] proved by Mahler's method that

$$\sum_{k \geq 0} \frac{p_k}{F_{2^k}}$$

is transcendental if $\{p_k\}_{k \geq 0}$ is not a constant sequence and that

$$\sum_{k \geq 0} \frac{p_k}{L_{2^k}}$$

is transcendental for any $\{p_k\}_{k \geq 0}$. Let $a \geq 1$ and d be integers. Recently, Nishioka, Tanaka, and Toshimitsu [12] proved that if $\{p_k\}_{k \geq 0}$ is not a constant sequence, the numbers

$$(12) \quad \sum'_{k \geq 0} \frac{p_k}{(F_{ad^k+h})^m} \quad (d \geq 2, h \in \mathbf{Z}, m \in \mathbf{N})$$

are algebraically independent, and if $\{p_k\}_{k \geq 0}$ is a constant sequence, the numbers (12) excepting the algebraic number $\sum'_{k \geq 0} p_k / F_{a2^k}$ are algebraically independent; and also the numbers

$$\sum'_{k \geq 0} \frac{p_k}{(L_{ad^k+h})^m} \quad (d \geq 2, h \in \mathbf{Z}, m \in \mathbf{N})$$

are algebraically independent for any $\{p_k\}_{k \geq 0}$. These results depend on the fact that the recurrences $\{F_k\}_{k \geq 0}$ and $\{L_k\}_{k \geq 0}$ are binary, namely these can be expressed as (9) with $r = 2$. In the case of $m = 1$, the transcendence of each of these numbers has already been proved by Becker and Töpfer [1]. For a general $\{R_k\}_{k \geq 0}$ not necessarily binary, only the transcendency result has been obtained also by Becker and Töpfer [1]:

If ρ_1, \dots, ρ_r are multiplicatively independent, then the number

$$\sum_{k \geq 0}' \frac{p_k}{R_{ad}^k}$$

is transcendental (cf. Remark 2 below).

Our results are concerned with the algebraic independence of the numbers (11) with $\{a_k\}_{k \geq 0}$ not a geometric progression. It is not necessary in our results to assume that ρ_1, \dots, ρ_r are multiplicatively independent. In what follows, N_0 denotes the set of nonnegative integers and \overline{Q} the field of algebraic numbers.

Theorem 3. *Let $\{R_k\}_{k \geq 0}$ be a linear recurrence represented as (9) with (10). Then the numbers*

$$(13) \quad \sum_{k \geq 0}' \frac{k^l \alpha^k}{(R_{a_k})^m} \quad (\alpha \in \overline{Q}^\times, l \in N_0, m \in N)$$

are algebraically independent.

Theorem 3 implies the algebraic independence of the numbers

$$\sum_{k \geq 0}' \frac{b_k}{(R_{a_k})^m} \quad (m \in N),$$

since a linear recurrence $\{b_k\}_{k \geq 0}$ of algebraic numbers not identically zero can be expressed as the linear combination of the sequences $\{k^l \alpha^k\}_{k \geq 0}$ ($\alpha \in \overline{Q}^\times, l \in N_0$) with algebraic coefficients.

REMARK 1. It is proved in Tanaka [13, Remark 4] that

$$a_k = c\gamma^k + o(\gamma^k),$$

where $\gamma > 1$ and $c > 0$, so that by (10) each sum in (13) converges.

REMARK 2. It still remains unsolved to prove the algebraic independence of the numbers (13) with $\{a_k\}_{k \geq 0}$ a geometric progression and without the assumption that ρ_1, \dots, ρ_r are multiplicatively independent.

Corollary 1. *In addition to the assumptions on $\Phi(X)$, suppose that $\Phi(X)$ has only simple roots. Then the numbers*

$$\sum_{k \geq 0}' \frac{k^l \alpha^k}{(a_{a_k})^m} \quad (\alpha \in \overline{Q}^\times, l \in N_0, m \in N)$$

are algebraically independent.

Proof. Since $\Phi(X)$ has only simple roots, a_k in place of R_k can be expressed as (9) with distinct roots ρ_1, \dots, ρ_r of $\Phi(X)$. And (10) is also satisfied by the condition on $\Phi(X)$ (see Nishioka [10, Theorem 2.8.1]). Thus we can take a_k as R_k . \square

EXAMPLE. Let $\{T_k\}_{k \geq 0}$ be so-called "Tribonacci" numbers defined by

$$T_{k+3} = T_{k+2} + T_{k+1} + T_k \quad (k = 0, 1, 2, \dots)$$

with the initial values $T_0 = 0, T_1 = 1,$ and $T_2 = 2$ and let $\{b_k\}_{k \geq 0}$ be a linear recurrence of algebraic numbers not identically zero. Then the numbers

$$\sum_{k \geq 1} \frac{b_k}{(T_{T_k})^m} \quad (m \in \mathbf{N})$$

are algebraically independent. We remark that T_k can be expressed as (9) with $r = 3$ and ρ_1, ρ_2, ρ_3 satisfying $\rho_1 \rho_2 \rho_3 = 1,$ so that $\rho_1, \rho_2,$ and ρ_3 are multiplicatively dependent.

If $\{R_k\}_{k \geq 0}$ is binary, we can deduce from Theorem 1 the algebraic independence of the numbers (11) for various $h,$ as in the case where $\{a_k\}_{k \geq 0}$ is a geometric progression stated above.

Theorem 4. Let $\{R_k\}_{k \geq 0}$ be a binary recurrence represented as

$$R_k = b_1 \rho_1^k + b_2 \rho_2^k \quad (k \geq 0),$$

where $b_1, b_2, \rho_1,$ and ρ_2 are nonzero algebraic numbers satisfying $|\rho_1| > \max\{1, |\rho_2|\}.$ Then the numbers

$$(14) \quad \sum_{k \geq 0}' \frac{k^l \alpha^k}{(R_{a_k+h})^m} \quad (\alpha \in \overline{\mathbf{Q}}^\times, l \in \mathbf{N}_0, m \in \mathbf{N}, h \in \mathbf{Z})$$

are algebraically independent.

Corollary 2. Let $\{R_k\}_{k \geq 0}$ be a binary recurrence defined by

$$R_{k+2} = A_1 R_{k+1} + A_2 R_k \quad (k \geq 0),$$

where A_1 and A_2 are real algebraic numbers satisfying $A_1 \neq 0, |A_2| \geq 1,$ and $\Delta = A_1^2 + 4A_2 > 0.$ Suppose that $\{R_k\}_{k \geq 0}$ is not a geometric progression. Then the numbers (14) are algebraically independent.

EXAMPLE. Let $\{F_k\}_{k \geq 0}$ be the Fibonacci numbers and let $\{b_k\}_{k \geq 0}$ be a linear recurrence of algebraic numbers not identically zero. Then the numbers

$$\sum'_{k \geq 0} \frac{b_k}{(F_{F_k+h})^m} \quad (h \in \mathbb{Z}, m \in \mathbb{N})$$

are algebraically independent.

REMARK 3. In the case where $\{a_k\}_{k \geq 0}$ is a geometric progression, a similar result to Corollary 2 is obtained by Nishioka [11] under the assumption that $R_0, R_1, A_1,$ and A_2 are rational integers and $m = 1$.

Next we state an application of Theorem 1 as well as Theorem 2. For the sequence $\{a_k\}_{k \geq 0}$, the author obtained the necessary and sufficient condition for the numbers $\sum_{k \geq 0} \alpha_1^{a_k}, \dots, \sum_{k \geq 0} \alpha_r^{a_k}$ to be algebraically dependent, where $\alpha_1, \dots, \alpha_r$ are algebraic numbers with $0 < |\alpha_i| < 1$ ($1 \leq i \leq r$). From Theorems 1 and 2 with Lemmas 1, 3, and 5, we can prove the following:

Theorem 5. *Suppose that the initial values a_0, \dots, a_{n-1} of $\{a_k\}_{k \geq 0}$ are positive. Let $\alpha_1, \dots, \alpha_r$ be algebraic numbers with $0 < |\alpha_i| < 1$ ($1 \leq i \leq r$) such that none of α_i/α_j ($1 \leq i < j \leq r$) is a root of unity. Then*

$$\sum_{k \geq 0} \alpha_i^{a_k}, \quad \sum_{k \geq 0} \frac{\alpha_i^{a_k}}{1 - \alpha_i^{a_k}}, \quad \prod_{k \geq 0} (1 - \alpha_i^{a_k}) \quad (1 \leq i \leq r)$$

are algebraically independent.

REMARK 4. The assumption that none of α_i/α_j ($1 \leq i < j \leq r$) is a root of unity cannot be removed even in the case where a_0, \dots, a_{n-1} have no common factor as the following example shows: Let $\{a_k\}_{k \geq 0}$ be a linear recurrence defined by

$$a_0 = 2, a_1 = 3, a_{k+2} = 6a_{k+1} + a_k \quad (k = 0, 1, 2, \dots).$$

We put

$$f(z) = \sum_{k \geq 0} z^{a_k}, \quad g(z) = \sum_{k \geq 0} \frac{z^{a_k}}{1 - z^{a_k}}, \quad h(z) = \prod_{k \geq 0} (1 - z^{a_k}).$$

Let α be an algebraic number with $0 < |\alpha| < 1$ and $\zeta = e^{\pi\sqrt{-1}/3} = (1 + \sqrt{-3})/2$. Then

$$\begin{aligned} 2f(\alpha) + f(\zeta\alpha) - f(\zeta^2\alpha) - 2f(\zeta^3\alpha) - f(\zeta^4\alpha) + f(\zeta^5\alpha) &= 0, \\ 2g(\alpha) + g(\zeta\alpha) - g(\zeta^2\alpha) - 2g(\zeta^3\alpha) - g(\zeta^4\alpha) + g(\zeta^5\alpha) &= 0, \end{aligned}$$

and

$$h(\alpha)^2 h(\zeta\alpha) h(\zeta^2\alpha)^{-1} h(\zeta^3\alpha)^{-2} h(\zeta^4\alpha)^{-1} h(\zeta^5\alpha) = 1,$$

since $a_{2k} \equiv 2 \pmod{6}$ and $a_{2k+1} \equiv 3 \pmod{6}$ for any $k \geq 0$.

REMARK 5. If $\{a_k\}_{k \geq 0}$ is a geometric progression, namely $a_k = ad^k$ ($k \geq 0$) for some integers $a \geq 1$ and $d \geq 2$, each of the numbers in Theorem 5 is transcendental by the theorem of Mahler [8] ; however Theorem 5 is not valid in this case, since there exist the following relations over $\overline{\mathbb{Q}}$: Let

$$f(z) = \sum_{k \geq 0} z^{ad^k}, \quad g(z) = \sum_{k \geq 0} \frac{z^{ad^k}}{1 - z^{ad^k}}, \quad h(z) = \prod_{k \geq 0} (1 - z^{ad^k}),$$

and let α be an algebraic number with $0 < |\alpha| < 1$. Then

$$f(\alpha) - f(\alpha^d) = \alpha^a, \quad g(\alpha) - g(\alpha^d) = \frac{\alpha^a}{1 - \alpha^a}, \quad \frac{h(\alpha)}{h(\alpha^d)} = 1 - \alpha^a,$$

where α/α^d is not a root of unity.

REMARK 6. The power series expansions of some of infinite products in Theorem 5 have interesting property. Beresin, Levine, and Lubell [2] proved that if

$$\prod_{k \geq 0} (1 - z^{F_{k+2}}) = \sum_{k \geq 0} \epsilon(k) z^k,$$

where $\{F_k\}_{k \geq 0}$ is the Fibonacci numbers, then $\epsilon(k) = 0$ or ± 1 for any $k \geq 0$.

2. Proofs of Theorems 3–5

In this section we derive Theorems 3, 4, and 5 from Theorems 1 and 2 by using Lemmas 1–5 below. Let $\Omega = (\omega_{ij})$ be an $n \times n$ matrix with nonnegative integer entries. Then the maximum ρ of the absolute values of the eigenvalues of Ω is itself an eigenvalue (cf. Gantmacher [4, p. 66, Theorem 3]). We suppose that Ω and a point $\alpha = (\alpha_1, \dots, \alpha_n)$, where α_i are nonzero algebraic numbers, have the following four properties:

- (I) Ω is non-singular and none of its eigenvalues is a root of unity, so that in particular $\rho > 1$.
- (II) Every entry of the matrix Ω^k is $O(\rho^k)$ as k tends to infinity.
- (III) If we put $\Omega^k \alpha = (\alpha_1^{(k)}, \dots, \alpha_n^{(k)})$, then

$$\log |\alpha_i^{(k)}| \leq -c\rho^k \quad (1 \leq i \leq n)$$

for all sufficiently large k , where c is a positive constant.

- (IV) For any nonzero power series $f(z)$ in n variables with complex coefficients which converges in some neighborhood of the origin, there are infinitely many positive integers k such that $f(\Omega^k \alpha) \neq 0$.

We note that the property (II) is satisfied if every eigenvalue of Ω of absolute value ρ is a simple root of the minimal polynomial of Ω .

Lemma 1 (Tanaka [13, Lemma 4, Proof of Theorem 2]). *Suppose that $\Phi(\pm 1) \neq 0$ and the ratio of any pair of distinct roots of $\Phi(X)$ is not a root of unity, where $\Phi(X)$ is the polynomial defined by (3). Let Ω be the matrix defined by (6) and β_1, \dots, β_s multiplicatively independent algebraic numbers with $0 < |\beta_j| < 1$ ($1 \leq j \leq s$). Let p be a positive integer and put*

$$\Omega' = \text{diag}(\underbrace{\Omega^p, \dots, \Omega^p}_s).$$

Then the matrix Ω' and the point

$$\beta = (\underbrace{1, \dots, 1}_{n-1}, \beta_1, \dots, \beta_s, \underbrace{1, \dots, 1}_{n-1})$$

have the properties (I)–(IV).

Lemma 2 (Nishioka [9]). *Let K be an algebraic number field. Suppose that $f_1(z), \dots, f_m(z) \in K[[z_1, \dots, z_n]]$ converge in an n -polydisc U around the origin and satisfy the functional equation of the form*

$$(15) \quad \begin{pmatrix} f_1(z) \\ \vdots \\ f_m(z) \end{pmatrix} = A \begin{pmatrix} f_1(\Omega z) \\ \vdots \\ f_m(\Omega z) \end{pmatrix} + \begin{pmatrix} b_1(z) \\ \vdots \\ b_m(z) \end{pmatrix},$$

where A is an $m \times m$ matrix with entries in K and $b_i(z) \in K(z_1, \dots, z_n)$. Assume that the $n \times n$ matrix Ω and a point $\alpha \in U$ whose components are nonzero algebraic numbers have the properties (I)–(IV). If $f_1(z), \dots, f_m(z)$ are algebraically independent over $K(z_1, \dots, z_n)$, then $f_1(\alpha), \dots, f_m(\alpha)$ are algebraically independent.

Lemma 3 (Kubota [5], see also Nishioka [10]). *Let K be an algebraic number field. Suppose that $f_1(z), \dots, f_m(z) \in K[[z_1, \dots, z_n]]$ converge in an n -polydisc U around the origin and satisfy the functional equations*

$$f_i(\Omega z) = a_i(z)f_i(z) + b_i(z) \quad (1 \leq i \leq m),$$

where $a_i(z), b_i(z) \in K(z_1, \dots, z_n)$ with $a_i(\mathbf{0}) \neq 0$. Assume that the $n \times n$ matrix Ω and a point $\alpha \in U$ whose components are nonzero algebraic numbers have

the properties (I)–(IV) and that $a_i(z)$ are defined and nonzero at $\Omega^k \alpha$ for all $k \geq 0$. If $f_1(z), \dots, f_m(z)$ are algebraically independent over $K(z_1, \dots, z_n)$, then $f_1(\alpha), \dots, f_m(\alpha)$ are algebraically independent.

Lemma 3 is essentially due to Kubota [5] and improved by Nishioka [10].

Let $L = C(z_1, \dots, z_n)$ and let M be the quotient field of $C[[z_1, \dots, z_n]]$. Let Ω be an $n \times n$ matrix with nonnegative integer entries having the property (I). We define an endomorphism $\tau : M \rightarrow M$ by

$$(16) \quad f^\tau(z) = f(\Omega z) \quad (f(z) \in M)$$

and a subgroup H of L^\times by

$$H = \{g^\tau g^{-1} | g \in L^\times\}.$$

Lemma 4 (Nishioka [9]). *Suppose that $f_{ij} \in M$ ($i = 1, \dots, k, j = 1, \dots, n(i)$) satisfy the functional equation of the form*

$$\begin{pmatrix} f_{i1} \\ \vdots \\ f_{in(i)} \end{pmatrix} = \begin{pmatrix} a_i & 0 & \cdots & 0 \\ a_{21}^{(i)} & a_i & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ a_{n(i)1}^{(i)} & \cdots & a_{n(i)n(i)-1}^{(i)} & a_i \end{pmatrix} \begin{pmatrix} f_{i1}^\tau \\ \vdots \\ f_{in(i)}^\tau \end{pmatrix} + \begin{pmatrix} b_{i1} \\ \vdots \\ b_{in(i)} \end{pmatrix},$$

where $a_i, a_{st}^{(i)} \in C, a_i \neq 0, a_{s s-1}^{(i)} \neq 0$, and $b_{ij} \in L$. If f_{ij} ($i = 1, \dots, k, j = 1, \dots, n(i)$) are algebraically dependent over L , then there exist a non-empty subset $\{i_1, \dots, i_r\}$ of $\{1, \dots, k\}$ and nonzero elements c_1, \dots, c_r of C such that

$$a_{i_1} = \cdots = a_{i_r}, c_1 f_{i_1 1} + \cdots + c_r f_{i_r 1} \in L.$$

Lemma 5 (Kubota [5], see also Nishioka [10]). *Let $f_i \in M$ ($i = 1, \dots, h$) satisfy*

$$f_i^\tau = a f_i + b_i,$$

where $a \in L^\times$ and $b_i \in L$ ($1 \leq i \leq h$), and let $f_i \in M^\times$ ($i = h+1, \dots, m$) satisfy

$$f_i^\tau = a_i f_i,$$

where $a_i \in L^\times$ ($h+1 \leq i \leq m$). Suppose that a, a_i , and b_i have the following properties:

(i) If $c_i \in C$ ($1 \leq i \leq h$) are not all zero, there is no element g of L such that

$$ag - g^r = \sum_{i=1}^h c_i b_i.$$

(ii) a_{h+1}, \dots, a_m are multiplicatively independent modulo H . Then the functions f_i ($1 \leq i \leq m$) are algebraically independent over L .

Proof of Theorem 3. Let ρ_1, \dots, ρ_r be the algebraic numbers in (9). There exist multiplicatively independent algebraic numbers β_1, \dots, β_s with $0 < |\beta_j| < 1$ ($1 \leq j \leq s$) such that

$$(17) \quad \rho_1^{-1} = \zeta_1 \prod_{j=1}^s \beta_j^{e_{1j}}, \rho_i^{-1} \rho_i = \zeta_i \prod_{j=1}^s \beta_j^{e_{ij}} \quad (2 \leq i \leq r),$$

where ζ_1, \dots, ζ_r are roots of unity and e_{ij} ($1 \leq i \leq r, 1 \leq j \leq s$) are nonnegative integers (cf. Loxton and van der Poorten [6], Nishioka [10]). Take a positive integer N such that $\zeta_i^N = 1$ for any i ($1 \leq i \leq r$). We can choose a positive integer p and a nonnegative integer k_0 such that $a_{k+p} \equiv a_k \pmod{N}$ for any $k \geq k_0$. By Remark 1, there exists a nonnegative integer k_1 such that $a_{k+1} > a_k$ for all $k \geq k_1$. Therefore by (9) and (10), there exists a nonnegative integer $q \geq \max\{k_0, k_1\}$ such that $R_{a_k} \neq 0$ for all $k \geq q$. Let $y_{j\lambda}$ ($1 \leq j \leq s, 1 \leq \lambda \leq n$) be variables and let $\mathbf{y}_j = (y_{j1}, \dots, y_{jn})$ ($1 \leq j \leq s$), $\mathbf{y} = (\mathbf{y}_1, \dots, \mathbf{y}_s)$. Define

$$f_m(x, \mathbf{y}) = \sum_{k \geq q} x^k \times \left(\zeta_1^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{1j}} / \left(b_1 + \sum_{i=2}^r b_i \zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}} \right) \right)^m \quad (m \geq 1),$$

where $P(z)$, $z = (z_1, \dots, z_n)$, is the monomial given by (4) and Ω is the matrix given by (6). Letting

$$D = x \frac{\partial}{\partial x}, \alpha \in \overline{\mathbf{Q}}^\times, \text{ and } \beta = (\underbrace{1, \dots, 1}_{n-1}, \beta_1, \dots, \dots, \underbrace{1, \dots, 1}_{n-1}, \beta_s),$$

we see that

$$D^l f_m(\alpha, \beta) = \sum_{k \geq q} k^l \alpha^k \left(\rho_1^{-a_k} / \left(b_1 + \sum_{i=2}^r b_i (\rho_1^{-1} \rho_i)^{a_k} \right) \right)^m = \sum_{k \geq q} \frac{k^l \alpha^k}{(R_{a_k})^m}.$$

Hence

$$\sum'_{k \geq 0} \frac{k^l \alpha^k}{(R_{\alpha_k})^m} - D^l f_m(\alpha, \beta) \in \overline{Q} \quad (\alpha \in \overline{Q}^\times, l \in N_0, m \in N),$$

and so it suffices to prove the algebraic independence of the values

$$D^l f_m(\alpha, \beta) \quad (\alpha \in \overline{Q}^\times, l \in N_0, m \in N).$$

Let

$$\Omega' = \text{diag}(\underbrace{\Omega^p, \dots, \Omega^p}_s).$$

Then $f_m(x, \mathbf{y})$ satisfies the functional equation

$$(18) \quad \begin{aligned} f_m(x, \mathbf{y}) &= x^p f_m(x, \Omega' \mathbf{y}) \\ &+ \sum_{k=q}^{p+q-1} x^k \left(\zeta_1^{\alpha_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{1j}} / \left(b_1 + \sum_{i=2}^r b_i \zeta_i^{\alpha_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}} \right) \right)^m, \end{aligned}$$

where $\Omega' \mathbf{y} = (\Omega^p \mathbf{y}_1, \dots, \Omega^p \mathbf{y}_s)$, and so $D^l f_m(x, \mathbf{y})$ ($l \geq 1$) satisfy

$$(19) \quad \begin{aligned} D^l f_m(x, \mathbf{y}) &= \sum_{\mu=0}^l \binom{l}{\mu} p^{l-\mu} x^p D^\mu f_m(x, \Omega' \mathbf{y}) \\ &+ \sum_{k=q}^{p+q-1} k^l x^k \left(\zeta_1^{\alpha_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{1j}} / \left(b_1 + \sum_{i=2}^r b_i \zeta_i^{\alpha_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}} \right) \right)^m. \end{aligned}$$

We assume that the values $D^l f_m(\alpha_\sigma, \beta)$ ($0 \leq l \leq L, 1 \leq m \leq M, 1 \leq \sigma \leq t$) are algebraically dependent, where $\alpha_1, \dots, \alpha_t$ are nonzero distinct algebraic numbers. It follows from (18) and (19) that $D^l f_m(\alpha_\sigma, \mathbf{y})$ ($0 \leq l \leq L, 1 \leq m \leq M, 1 \leq \sigma \leq t$) satisfy the functional equation of the form (15), so that they are algebraically dependent over $\overline{Q}(\mathbf{y})$ by Lemmas 1 and 2. Hence we see by Lemma 4 that

$$(20) \quad \alpha_1^p = \dots = \alpha_t^p$$

and $f_m(\alpha_\sigma, \mathbf{y})$ ($1 \leq m \leq M, 1 \leq \sigma \leq \nu$) are linearly dependent over \overline{Q} modulo $\overline{Q}(\mathbf{y})$, changing the indices σ ($1 \leq \sigma \leq t$) if necessary. Thus there are algebraic numbers $c_{m\sigma}$ ($1 \leq m \leq M, 1 \leq \sigma \leq \nu$), not all zero, such that

$$F(\mathbf{y}) := \sum_{m=1}^M \sum_{\sigma=1}^{\nu} c_{m\sigma} f_m(\alpha_\sigma, \mathbf{y}) \in \overline{Q}(\mathbf{y}).$$

Since $F(\mathbf{y}) \in \overline{\mathcal{Q}}[[\mathbf{y}]] \cap \overline{\mathcal{Q}}(\mathbf{y})$, there are $A(\mathbf{y}), B(\mathbf{y}) \in \overline{\mathcal{Q}}[\mathbf{y}]$ such that

$$F(\mathbf{y}) = A(\mathbf{y})/B(\mathbf{y}), \quad B(\mathbf{0}) \neq 0$$

(see Nishioka [9, Lemma 4]). Letting $\mathbf{y}_1 = \dots = \mathbf{y}_s = \mathbf{z} = (z_1, \dots, z_n)$, we have

$$\begin{aligned} G(\mathbf{z}) &= F(\underbrace{\mathbf{z}, \dots, \mathbf{z}}_s) \\ &= \sum_{k \geq q} \sum_{m=1}^M \left(\sum_{\sigma=1}^{\nu} c_{m\sigma} \alpha_{\sigma}^k \right) \left(\zeta_1^{a_k} P(\Omega^k \mathbf{z})^{E_1} / \left(b_1 + \sum_{i=2}^r b_i \zeta_i^{a_k} P(\Omega^k \mathbf{z})^{E_i} \right) \right)^m \\ &\in \overline{\mathcal{Q}}(z_1, \dots, z_n), \end{aligned}$$

where $E_i = \sum_{j=1}^s e_{ij} \in \mathbf{N}$ ($1 \leq i \leq r$), since e_{i1}, \dots, e_{is} are not all zero for each i . Letting $\sum_{\sigma=1}^{\nu} c_{m\sigma} \alpha_{\sigma}^k = d_m(k) \alpha_1^k$ ($1 \leq m \leq M$), we find

$$d_m(k+p) = d_m(k) \quad (k \geq 0)$$

by (20). Then $G(\mathbf{z})$ satisfies the functional equation

$$\begin{aligned} G(\mathbf{z}) &= \alpha_1^p G(\Omega^p \mathbf{z}) \\ &\quad + \sum_{k=q}^{p+q-1} \sum_{m=1}^M d_m(k) \alpha_1^k \left(\zeta_1^{a_k} P(\Omega^k \mathbf{z})^{E_1} / \left(b_1 + \sum_{i=2}^r b_i \zeta_i^{a_k} P(\Omega^k \mathbf{z})^{E_i} \right) \right)^m, \end{aligned}$$

so that by Theorem 1,

$$\begin{aligned} Q_k(X) &= \sum_{m=1}^M d_m(k) \alpha_1^k \\ &\quad \times \left(\zeta_1^{a_k} X^{E_1} / \left(b_1 + \sum_{i=2}^r b_i \zeta_i^{a_k} X^{E_i} \right) \right)^m \in \overline{\mathcal{Q}} \quad (q \leq k \leq p+q-1). \end{aligned}$$

Hence

$$d_m(k) = 0 \quad (1 \leq m \leq M, q \leq k \leq p+q-1),$$

since $\text{ord}_{X=0} \left(\zeta_1^{a_k} X^{E_1} / (b_1 + \sum_{i=2}^r b_i \zeta_i^{a_k} X^{E_i}) \right)^m = mE_1$ ($1 \leq m \leq M$). Letting $\eta_{\sigma} = \alpha_{\sigma} / \alpha_1$ ($1 \leq \sigma \leq \nu$), we see that $\eta_1, \dots, \eta_{\nu}$ are distinct p -th roots of unity by (20) and that $d_m(k) = \sum_{\sigma=1}^{\nu} c_{m\sigma} \eta_{\sigma}^k = 0$ ($q \leq k \leq p+q-1$), which holds only if $c_{m1} = \dots = c_{m\nu} = 0$. This is a contradiction, since $c_{m\sigma}$ ($1 \leq m \leq M, 1 \leq \sigma \leq \nu$) are not all zero, and the proof of the theorem is completed. \square

Proof of Theorem 4. We assume that

$$\sum'_{k \geq 0} \frac{k^l \alpha_\sigma^k}{(R_{a_k+h})^m} \quad (1 \leq \sigma \leq t, 0 \leq l \leq L, H \leq h \leq H, 1 \leq m \leq M)$$

are algebraically dependent, where $\alpha_1, \dots, \alpha_t$ are nonzero distinct algebraic numbers. Since $|\rho_1| > \max\{1, |\rho_2|\}$, there exists a nonnegative integer $q \geq \max\{k_0, k_1\}$ such that $R_{a_k+h} \neq 0$ for any h ($-H \leq h \leq H$) and for all $k \geq q$. Define

$$f_{h,m}(x, \mathbf{y}) = \sum_{k \geq q} x^k \times \left(\zeta_1^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{1j}} / \left(1 + b_1^{-1} b_2 (\rho_1^{-1} \rho_2)^h \zeta_2^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{2j}} \right) \right)^m \quad (-H \leq h \leq H, 1 \leq m \leq M),$$

where $P(z), \Omega$ are given by (4), (6), respectively, and the roots of unity ζ_1, ζ_2 and the nonnegative integers e_{ij} ($i = 1, 2, 1 \leq j \leq s$) are determined by (17). Letting D and β be as in the proof of Theorem 1, we see that

$$\begin{aligned} & (b_1^{-1} \rho_1^{-h})^m D^l f_{h,m}(\alpha_\sigma, \beta) \\ &= \sum_{k \geq q} k^l \alpha_\sigma^k (b_1^{-1} \rho_1^{-h} \rho_1^{-a_k} / (1 + b_1^{-1} b_2 (\rho_1^{-1} \rho_2)^h (\rho_1^{-1} \rho_2)^{a_k}))^m \\ &= \sum_{k \geq q} \frac{k^l \alpha_\sigma^k}{(R_{a_k+h})^m}. \end{aligned}$$

Hence

$$\begin{aligned} & \sum'_{k \geq 0} \frac{k^l \alpha_\sigma^k}{(R_{a_k+h})^m} - (b_1^{-1} \rho_1^{-h})^m D^l f_{h,m}(\alpha_\sigma, \beta) \in \overline{\mathbf{Q}} \\ & (0 \leq l \leq L, -H \leq h \leq H, 1 \leq m \leq M, 1 \leq \sigma \leq t), \end{aligned}$$

and so $D^l f_{h,m}(\alpha_\sigma, \beta)$ ($0 \leq l \leq L, H \leq h \leq H, 1 \leq m \leq M, 1 \leq \sigma \leq t$) are algebraically dependent. By the same way as in the proof of Theorem 1, we see that

$$(21) \quad \alpha_1^p = \dots = \alpha_\nu^p$$

and $f_{h,m}(\alpha_\sigma, \mathbf{y})$ ($-H \leq h \leq H, 1 \leq m \leq M, 1 \leq \sigma \leq \nu$) are linearly dependent over $\overline{\mathbf{Q}}$ modulo $\overline{\mathbf{Q}}(\mathbf{y})$, changing the indices σ ($1 \leq \sigma \leq t$) if necessary. Thus there are algebraic numbers $c_{hm\sigma}$ ($-H \leq h \leq H, 1 \leq m \leq M, 1 \leq \sigma \leq \nu$), not all zero, such that

$$F(\mathbf{y}) := \sum_{h=-H}^H \sum_{m=1}^M \sum_{\sigma=1}^\nu c_{hm\sigma} f_{h,m}(\alpha_\sigma, \mathbf{y}) \in \overline{\mathbf{Q}}(\mathbf{y}).$$

Letting $y_1 = \dots = y_s = z = (z_1, \dots, z_n)$, we have

$$\begin{aligned} & G(z) \\ &= F(\underbrace{z, \dots, z}_s) \\ &= \sum_{k \geq q} \sum_{h=-H}^H \sum_{m=1}^M \left(\sum_{\sigma=1}^{\nu} c_{hm\sigma} \alpha_{\sigma}^k \right) \\ &\quad \times (\zeta_1^{a_k} P(\Omega^k z)^{E_1} / (1 + b_1^{-1} b_2 (\rho_1^{-1} \rho_2)^h \zeta_2^{a_k} P(\Omega^k z)^{E_2}))^m \\ &\in \overline{Q}(z_1, \dots, z_n), \end{aligned}$$

where $E_i = \sum_{j=1}^s e_{ij} \in N$ ($i = 1, 2$), since e_{i1}, \dots, e_{is} are not all zero for each i . Letting $\sum_{\sigma=1}^{\nu} c_{hm\sigma} \alpha_{\sigma}^k = d_{hm}(k) \alpha_1^k$ ($-H \leq h \leq H, 1 \leq m \leq M$), we find

$$d_{hm}(k+p) = d_{hm}(k) \quad (k \geq 0)$$

by (21). Then $G(z)$ satisfies the functional equation

$$\begin{aligned} & G(z) \\ &= \alpha_1^p G(\Omega^p z) \\ &\quad + \sum_{k=q}^{p+q-1} \sum_{h=-H}^H \sum_{m=1}^M d_{hm}(k) \alpha_1^k \\ &\quad \times (\zeta_1^{a_k} P(\Omega^k z)^{E_1} / (1 + b_1^{-1} b_2 (\rho_1^{-1} \rho_2)^h \zeta_2^{a_k} P(\Omega^k z)^{E_2}))^m, \end{aligned}$$

so that by Theorem 1,

$$\begin{aligned} Q_k(X) &= \sum_{h=-H}^H \sum_{m=1}^M d_{hm}(k) \alpha_1^k (\zeta_1^{a_k} X^{E_1} / (1 + b_1^{-1} b_2 (\rho_1^{-1} \rho_2)^h \zeta_2^{a_k} X^{E_2}))^m \\ &\in \overline{Q} \quad (q \leq k \leq p+q-1). \end{aligned}$$

Hence

$$d_{hm}(k) = 0 \quad (-H \leq h \leq H, 1 \leq m \leq M, q \leq k \leq p+q-1),$$

since $Q_k(X)$ has some poles if $d_{hm}(k)$ ($-H \leq h \leq H, 1 \leq m \leq M$) are not all zero. The rest of the proof is similar to that of the proof of Theorem 3. \square

Proof of Theorem 5. There exist multiplicatively independent algebraic numbers β_1, \dots, β_s with $0 < |\beta_j| < 1$ ($1 \leq j \leq s$) such that

$$(22) \quad \alpha_i = \zeta_i \prod_{j=1}^s \beta_j^{e_{ij}} \quad (1 \leq i \leq r),$$

where ζ_1, \dots, ζ_r are roots of unity and e_{ij} ($1 \leq i \leq r, 1 \leq j \leq s$) are nonnegative integers. Take a positive integer N such that $\zeta_i^N = 1$ for any i ($1 \leq i \leq r$). We can choose a positive integer p and a nonnegative integer q such that $a_{k+p} \equiv a_k \pmod{N}$ for any $k \geq q$. Let $y_{j\lambda}$ ($1 \leq j \leq s, 1 \leq \lambda \leq n$) be variables and let $\mathbf{y}_j = (y_{j1}, \dots, y_{jn})$ ($1 \leq j \leq s$), $\mathbf{y} = (\mathbf{y}_1, \dots, \mathbf{y}_s)$. Define

$$f_i(\mathbf{y}) = \sum_{k \geq q} \zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}},$$

$$g_i(\mathbf{y}) = \sum_{k \geq q} \frac{\zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}}}{1 - \zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}}},$$

and

$$h_i(\mathbf{y}) = \prod_{k \geq q} \left(1 - \zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}} \right) \quad (1 \leq i \leq r),$$

where $P(z)$ and Ω are defined by (4) and (6), respectively. Letting

$$\beta = (\underbrace{1, \dots, 1}_{n-1}, \beta_1, \dots, \beta_s, \underbrace{1, \dots, 1}_{n-1}),$$

we see that

$$f_i(\beta) = \sum_{k \geq q} \alpha_i^{a_k}, \quad g_i(\beta) = \sum_{k \geq q} \frac{\alpha_i^{a_k}}{1 - \alpha_i^{a_k}}, \quad h_i(\beta) = \prod_{k \geq q} (1 - \alpha_i^{a_k}),$$

and so it suffices to prove the algebraic independence of the values $f_i(\beta), g_i(\beta), h_i(\beta)$ ($1 \leq i \leq r$). Let

$$\Omega' = \text{diag}(\underbrace{\Omega^p, \dots, \Omega^p}_s).$$

Then $f_i(\mathbf{y}), g_i(\mathbf{y}), h_i(\mathbf{y})$ ($1 \leq i \leq r$) satisfy the functional equations

$$f_i(\mathbf{y}) = f_i(\Omega' \mathbf{y}) + \sum_{k=q}^{p+q-1} \zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}},$$

$$g_i(\mathbf{y}) = g_i(\Omega' \mathbf{y}) + \sum_{k=q}^{p+q-1} \frac{\zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}}}{1 - \zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}}},$$

and

$$h_i(\mathbf{y}) = \left(\prod_{k=q}^{p+q-1} \left(1 - \zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}} \right) \right) h_i(\Omega' \mathbf{y}),$$

where $\Omega' \mathbf{y} = (\Omega^p \mathbf{y}_1, \dots, \Omega^p \mathbf{y}_s)$. We assume that the values $f_i(\beta), g_i(\beta), h_i(\beta)$ ($1 \leq i \leq r$) are algebraically dependent. Then the functions $f_i(\mathbf{y}), g_i(\mathbf{y}), h_i(\mathbf{y})$ ($1 \leq i \leq r$) are algebraically dependent over $\overline{\mathcal{Q}}(\mathbf{y})$ by Lemmas 1 and 3. Hence by Lemma 5 at least one of the following two cases arises:

(i) There are algebraic numbers b_i, c_i ($1 \leq i \leq r$), not all zero, and $F(\mathbf{y}) \in \overline{\mathcal{Q}}(\mathbf{y})$ such that

$$(23) \quad F(\mathbf{y}) = F(\Omega' \mathbf{y}) + \sum_{k=q}^{p+q-1} \sum_{i=1}^r \left(b_i \zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}} + \frac{c_i \zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}}}{1 - \zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}}} \right).$$

(ii) There are rational integers d_i ($1 \leq i \leq r$), not all zero, and $G(\mathbf{y}) \in \overline{\mathcal{Q}}(\mathbf{y}) \setminus \{0\}$ such that

$$(24) \quad G(\mathbf{y}) = \left(\prod_{k=q}^{p+q-1} \prod_{i=1}^r \left(1 - \zeta_i^{a_k} \prod_{j=1}^s P(\Omega^k \mathbf{y}_j)^{e_{ij}} \right)^{d_i} \right) G(\Omega' \mathbf{y}).$$

Let M be a positive integer and let

$$\mathbf{y}_j = (y_{j1}, \dots, y_{jn}) = (z_1^{M^j}, \dots, z_n^{M^j}) \quad (1 \leq j \leq s),$$

where M is so large that the following two properties are both satisfied:

- (I) If $(e_{i1}, \dots, e_{is}) \neq (e_{i'1}, \dots, e_{i's})$, then $\sum_{j=1}^s e_{ij} M^j \neq \sum_{j=1}^s e_{i'j} M^j$.
- (II) $F^*(\mathbf{z}) = F(z_1^M, \dots, z_n^M, \dots, z_1^{M^s}, \dots, z_n^{M^s}) \in \overline{\mathcal{Q}}(z_1, \dots, z_n)$,
 $G^*(\mathbf{z}) = G(z_1^M, \dots, z_n^M, \dots, z_1^{M^s}, \dots, z_n^{M^s}) \in \overline{\mathcal{Q}}(z_1, \dots, z_n) \setminus \{0\}$.

Then by (23) and (24), at least one of the following two functional equations holds:

$$(i) \quad F^*(\mathbf{z}) = F^*(\Omega^p \mathbf{z}) + \sum_{k=q}^{p+q-1} \sum_{i=1}^r \left(b_i \zeta_i^{a_k} P(\Omega^k \mathbf{z})^{E_i} + \frac{c_i \zeta_i^{a_k} P(\Omega^k \mathbf{z})^{E_i}}{1 - \zeta_i^{a_k} P(\Omega^k \mathbf{z})^{E_i}} \right).$$

$$(ii) \quad G^*(\mathbf{z}) = \left(\prod_{k=q}^{p+q-1} \prod_{i=1}^r \left(1 - \zeta_i^{a_k} P(\Omega^k \mathbf{z})^{E_i} \right)^{d_i} \right) G(\Omega^p \mathbf{z}).$$

Here $E_i = \sum_{j=1}^s e_{ij} M^j$ ($1 \leq i \leq r$) are distinct positive integers by the property (I), since none of α_i/α_j ($1 \leq i < j \leq r$) is a root of unity. By Theorems 1, 2, and the property (II), at least one of the following two properties are satisfied:

(i) For any k ($q \leq k \leq p+q-1$),

$$(25) \quad \sum_{i=1}^r \left(b_i \zeta_i^{a_k} X^{E_i} + \frac{c_i \zeta_i^{a_k} X^{E_i}}{1 - \zeta_i^{a_k} X^{E_i}} \right) = \sum_{i=1}^r \left(b_i \zeta_i^{a_k} X^{E_i} + c_i \sum_{l=1}^{\infty} (\zeta_i^{a_k} X^{E_i})^l \right) \in \overline{\mathcal{Q}}.$$

(ii) For any k ($q \leq k \leq p+q-1$),

$$(26) \quad \prod_{i=1}^r (1 - \zeta_i^{a_k} X^{E_i})^{d_i} = \gamma_k \in \overline{\mathbb{Q}}^\times.$$

Suppose first that (i) is satisfied. Then we show that $c_i = 0$ ($1 \leq i \leq r$). Assume contrary that c_1, \dots, c_r are not all zero. Let $S = \{i \in \{1, \dots, r\} | c_i \neq 0\}$ and let $i' \in S$ be the index such that $E_{i'} < E_i$ for any $i \in S \setminus \{i'\}$. Since $(E_1 \cdots E_r + 1)E_{i'}$ is not divided by any E_i with $i \in S \setminus \{i'\}$, the term $c_{i'}(\zeta_{i'}^{a_k} X^{E_{i'}})^{E_1 \cdots E_r + 1}$ does not cancel in (25), which is a contradiction. Hence $c_i = 0$ ($1 \leq i \leq r$) and so b_1, \dots, b_r are not all zero, which is also a contradiction, since E_1, \dots, E_r are distinct. Next suppose that (ii) is satisfied. Taking the logarithmic derivative of (26), we get

$$\sum_{i=1}^r \frac{-d_i E_i \zeta_i^{a_k} X^{E_i-1}}{1 - \zeta_i^{a_k} X^{E_i}} = 0 \quad (q \leq k \leq p + q - 1).$$

This is a contradiction, since $\text{ord}_{X=0} E_i \zeta_i^{a_k} X^{E_i-1} / (1 - \zeta_i^{a_k} X^{E_i}) = E_i - 1$ ($1 \leq i \leq r$), and the proof of the theorem is completed. □

3. Proofs of Theorems 1 and 2

We need several lemmas to prove Theorems 1 and 2. Use the same notations as in the preceding section, define an endomorphism $\tau : M \rightarrow M$ by (16), and adopt the usual vector notation, that is, if $I = (i_1, \dots, i_n) \in \mathbb{Z}^n$, we write $z^I = z_1^{i_1} \cdots z_n^{i_n}$. We denote by $C[z_1, \dots, z_n]$ the ring of polynomials in variables z_1, \dots, z_n with coefficients in C .

Lemma 6 (Nishioka [10]). *If $A, B \in C[z_1, \dots, z_n]$ are coprime, then $(A^\tau, B^\tau) = z^I$, where $I \in \mathbb{N}_0^n$.*

Lemma 7 (Nishioka [10]). *Let Ω be an $n \times n$ matrix with nonnegative integer entries which has the property (I). Let $R(z)$ be a nonzero polynomial in $\overline{C}[z_1, \dots, z_n]$ and $\mathbf{x} = (x_1, \dots, x_n)$ an element of \overline{C}^n with $x_i \neq 0$ for any i ($1 \leq i \leq n$). We put*

$$R(z) = \sum_{I=(i_1, \dots, i_n) \in \Lambda} c_I z^I \quad (c_I \neq 0).$$

If $R(\Omega^k \mathbf{x}) = 0$ for infinitely many positive integers k , then there exist distinct elements $I, J \in \Lambda$ and positive integers a, b such that

$$\mathbf{x}^{(I-J)\Omega^a(\Omega^{bk}-E)} = 1$$

for all $k \geq 0$, where E is the identity matrix.

Lemma 8 (Nishioka [9]). *If $g \in M$ satisfies*

$$g^\tau = cg + d \quad (c, d \in C),$$

then $g \in C$.

Lemma 9. *Let $\{a_k\}_{k \geq 0}$ be a linear recurrence satisfying (2). Suppose that $\{a_k\}_{k \geq 0}$ is not a geometric progression. Assume that the ratio of any pair of distinct roots of $\Phi(X)$ is not a root of unity. Then the sequence $\{a_k\}_{k \geq 0}$ does not satisfy the linear recurrence relation of the form*

$$a_{k+l} = ca_k \quad (k \geq 0),$$

where l is a positive integer and c is a nonzero rational number.

Proof. If $l = 1$, then $a_k = a_0c^k$ ($k \geq 0$), which contradicts the assumption in the lemma. If $l \geq 2$, then at least two of the roots of $\Psi(X) = X^l - c$ are those of $\Phi(X)$. This also contradicts the assumption, since the ratio of any pair of distinct roots of $\Psi(X)$ is a root of unity. □

Lemma 10. *Let $\mathbf{u} = (u_1, \dots, u_n)$ satisfy $\text{trans. deg}_C C(\mathbf{u}) = n - 1$. If $\mathbf{u}^I, \mathbf{u}^J \in C^\times$, where $I, J \in \mathbf{Z}^n \setminus \{\mathbf{0}\}$, then I and J are proportional, i.e., there exists a nonzero rational number r such that $I = rJ$.*

Proof. Suppose contrary there are $I = (i_1, \dots, i_n), J = (j_1, \dots, j_n) \in \mathbf{Z}^n \setminus \{\mathbf{0}\}$ such that $\mathbf{u}^I, \mathbf{u}^J \in C^\times$ and I, J are not proportional. Assume that $j_\lambda \neq 0$. Then u_λ is algebraic over the field $C(u_1, \dots, u_{\lambda-1}, u_{\lambda+1}, \dots, u_n)$. Since $(\mathbf{u}^I)^{j_\lambda} (\mathbf{u}^J)^{-i_\lambda} = \mathbf{u}^{j_\lambda I - i_\lambda J} \in C^\times$ and $j_\lambda I - i_\lambda J$ is a nonzero vector whose λ -th component is zero, $u_1, \dots, u_{\lambda-1}, u_{\lambda+1}, \dots, u_n$ are algebraically dependent over C . Hence $\text{trans. deg}_C C(\mathbf{u}) \leq n - 2$, which is a contradiction. □

Lemma 11. *If $k_1, k_2 \in \mathbf{N}_0$ are distinct, then $P(\Omega^{k_1} z) - \gamma_1$ and $P(\Omega^{k_2} z) - \gamma_2$ are coprime, where $P(z)$ is the monomial defined by (4), Ω is the matrix defined by (6), and $\gamma_1, \gamma_2 \in C^\times$.*

Proof. Suppose contrary there exists an irreducible $T(z) \in C[z_1, \dots, z_n] \setminus C$ which divides both $P(\Omega^{k_1} z) - \gamma_1$ and $P(\Omega^{k_2} z) - \gamma_2$. We may assume that $k_1 > k_2$. Let $\mathbf{u} = (u_1, \dots, u_n)$ be a generic point of the algebraic variety defined by $T(z)$ over C . Then $T(\mathbf{u}) = 0$ and $\text{trans. deg}_C C(\mathbf{u}) = n - 1$. Since $T(\mathbf{u}) = 0$,

$$P(\Omega^{k_1} \mathbf{u}) = u_1^{a_{k_1+n-1}} \dots u_n^{a_{k_1}} = \gamma_1$$

and

$$P(\Omega^{k_2} \mathbf{u}) = u_1^{a_{k_2+n-1}} \cdots u_n^{a_{k_2}} = \gamma_2.$$

By Lemma 10, there exists a nonzero rational number c such that $(a_{k_1+n-1}, \dots, a_{k_1}) = c(a_{k_2+n-1}, \dots, a_{k_2})$. Hence by (2), $\{a_k\}_{k \geq 0}$ satisfies the linear recurrence relation $a_{k+k_1-k_2} = ca_k$ ($k = 0, 1, 2, \dots$), which contradicts Lemma 9. \square

Lemma 12. *Let Ω be an $n \times n$ matrix with nonnegative integer entries which has the property (I). Let $R(\mathbf{z})$ be a nonzero polynomial in $C[z_1, \dots, z_n]$. If $R(\Omega \mathbf{z})$ divides $R(\mathbf{z})z^I$, where $I \in \mathbf{N}_0^n$, then $R(\mathbf{z})$ is a monomial in z_1, \dots, z_n .*

Proof. We can put

$$R(\mathbf{z}) = z^J \prod_{i=1}^{\nu} g_i(\mathbf{z})^{e_i},$$

where $J \in \mathbf{N}_0^n$, e_i ($1 \leq i \leq \nu$) are positive integers, and $g_1(\mathbf{z}), \dots, g_{\nu}(\mathbf{z})$ are distinct irreducible polynomials and not monomials. For each i ($1 \leq i \leq \nu$), $g_i(\Omega \mathbf{z})$ can be written as

$$g_i(\Omega \mathbf{z}) = h_i(\mathbf{z})z^{H_i},$$

where $h_i(\mathbf{z}) \in C[z_1, \dots, z_n] \setminus C$ is not divided by z_1, \dots, z_n , and $H_i \in \mathbf{N}_0^n$. Since $z^{J\Omega} \prod_{i=1}^{\nu} (h_i(\mathbf{z})z^{H_i})^{e_i}$ divides $z^{I+J} \prod_{i=1}^{\nu} g_i(\mathbf{z})^{e_i}$,

$$(27) \quad \prod_{i=1}^{\nu} h_i(\mathbf{z})^{e_i} \mid \prod_{i=1}^{\nu} g_i(\mathbf{z})^{e_i}.$$

Hence $h_1(\mathbf{z}), \dots, h_{\nu}(\mathbf{z})$ are irreducible, otherwise we can deduce a contradiction, comparing the numbers of prime factors in (27); thereby

$$\prod_{i=1}^{\nu} h_i(\mathbf{z})^{e_i} = \xi \prod_{i=1}^{\nu} g_i(\mathbf{z})^{e_i},$$

where ξ is a nonzero element of C . Therefore

$$R(\Omega \mathbf{z}) = \xi R(\mathbf{z})z^H, H = J(\Omega - E) + \sum_{i=1}^{\nu} e_i H_i \in \mathbf{Z}^n.$$

Let $D = |\det(\Omega - E)|$. Then D is a positive integer, since the matrix Ω has no roots of unity as its eigenvalues. We extend the endomorphism $\tau : M \rightarrow M$ to the quotient field M' of formal power series ring $C[[z_1^{1/D}, \dots, z_n^{1/D}]]$ by the usual way. Since the monomial $S(\mathbf{z}) = z^{H(\Omega - E)^{-1}} \in M'$ satisfies $S^{\tau}(\mathbf{z}) = S(\mathbf{z})z^H$, we see that $F(\mathbf{z}) =$

$R(z)/S(z) \in M'$ satisfies $F^r(z) = \xi F(z)$ and so $F(z) \in C$ by Lemma 8, which means that $R(z)$ is a monomial in z_1, \dots, z_n . \square

Proof of Theorem 1. Let $\gamma_1, \dots, \gamma_t$ be the distinct roots of the least common denominator of $Q_k(X)$ ($q \leq k \leq p + q - 1$). Then $\gamma_1, \dots, \gamma_t$ are nonzero elements of \overline{C} . There exists a positive integer M such that

$$R(z) = \left(\prod_{k=q}^{p+q-1} \prod_{j=1}^t (P(\Omega^k z) - \gamma_j)^M \right) \sum_{k=q}^{p+q-1} Q_k(P(\Omega^k z)) \in \overline{C}[z_1, \dots, z_n].$$

Letting $G(z) = A(z)/B(z)$, where $A(z)$ and $B(z)$ are coprime polynomials in $\overline{C}[z_1, \dots, z_n]$, we have

$$\begin{aligned} & A(z)B(\Omega^p z) \prod_{k=q}^{p+q-1} \prod_{j=1}^t (P(\Omega^k z) - \gamma_j)^M \\ &= \alpha A(\Omega^p z)B(z) \prod_{k=q}^{p+q-1} \prod_{j=1}^t (P(\Omega^k z) - \gamma_j)^M + R(z)B(z)B(\Omega^p z) \end{aligned}$$

by (7). We can put $(A(\Omega^p z), B(\Omega^p z)) = z^I$, where $I \in \mathbf{N}_0^n$, by Lemma 6. Then

$$(28) \quad B(\Omega^p z) | B(z) z^I \prod_{k=q}^{p+q-1} \prod_{j=1}^t (P(\Omega^k z) - \gamma_j)^M$$

and

$$(29) \quad B(z) | B(\Omega^p z) \prod_{k=q}^{p+q-1} \prod_{j=1}^t (P(\Omega^k z) - \gamma_j)^M.$$

First we prove that $G(z) \in \overline{C}[z_1, \dots, z_n]$. For this purpose, we show that $B(\Omega^p z)$ divides $B(z)z^I$. Otherwise, by (28), there exists a prime factor $T(z) \in \overline{C}[z_1, \dots, z_n]$ of $B(\Omega^p z)$ such that

$$(30) \quad T(z) | (P(\Omega^{k_0} z) - \gamma_{j_0})$$

for some k_0 ($q \leq k_0 \leq p + q - 1$) and for some j_0 ($1 \leq j_0 \leq t$). Let $\mathbf{u} = (u_1, \dots, u_n)$ be a generic point of the algebraic variety defined by $T(z)$ over \overline{C} . Then $T(\mathbf{u}) = 0$ and

$$\text{trans. deg}_{\overline{C}} \overline{C}(\mathbf{u}) = n - 1.$$

Letting $\mathbf{z} = \mathbf{u}$ in (30), we see that

$$(31) \quad P(\Omega^{k_0} \mathbf{u}) = u_1^{a_{k_0+n-1}} \dots u_n^{a_{k_0}} = \gamma_{j_0}.$$

Since $T(z)$ divides $B(\Omega^p z)$ and $B(\Omega^p z)$ divides $B(\Omega^{2p} z) \prod_{k=q}^{p+q-1} \prod_{j=1}^t (P(\Omega^{k+p} z) - \gamma_j)^M$ by (29),

$$T(z) | B(\Omega^{2p} z) \prod_{k=q}^{p+q-1} \prod_{j=1}^t (P(\Omega^{k+p} z) - \gamma_j)^M.$$

Therefore $T(z)$ divides $B(\Omega^{2p} z)$ by Lemma 11 with (30). Continuing this process, we see that $T(z)$ divides $B(\Omega^{pk} z)$ and so $B(\Omega^{pk} \mathbf{u}) = 0$ for all positive integers k . Since $u_\lambda \neq 0$ ($1 \leq \lambda \leq n$), by Lemmas 1 and 7, there exist a nonzero n -dimensional vector \mathbf{v} with rational integer components and positive integers d, e such that $\mathbf{u} \mathbf{v}^{\Omega^e (\Omega^{dk} - E)} = 1$ for all $k \geq 0$, where E is the identity matrix. Then

$$\mathbf{u} \mathbf{v}^{(\Omega^d - E) \Omega^{dk+e}} = 1$$

for all $k \geq 0$. Letting $\mathbf{v}(\Omega^d - E) \Omega^e = (b_{n-1}, \dots, b_0)$ and letting $\{b_k\}_{k \geq 0}$ be a linear recurrence defined by (2) with the initial values b_0, \dots, b_{n-1} , we have

$$(32) \quad u_1^{b_{dk+n-1}} \dots u_n^{b_{dk}} = 1$$

for all $k \geq 0$. Therefore by Lemma 10, together with (2), $\{b_k\}_{k \geq 0}$ satisfies the linear recurrence relation

$$(33) \quad b_{k+d} = cb_k \quad (k \geq 0),$$

where c is a nonzero rational number. On the other hand, there exists a nonzero rational number c' such that $(a_{k_0+n-1}, \dots, a_{k_0}) = c'(b_{n-1}, \dots, b_0)$ by (31), (32), and Lemma 10. Hence by (2), we have

$$(34) \quad a_{k+k_0} = c'b_k \quad (k \geq 0).$$

By (33) and (34), $a_{k+d} = ca_k$ for all $k \geq k_0$. Then by (2), $a_{k+d} = ca_k$ ($k \geq 0$), which contradicts Lemma 9, and so we can conclude that $B(\Omega^p z)$ divides $B(z)z^l$. Therefore $B(z)$ is a monomial in z_1, \dots, z_n by Lemmas 1 and 12. Hence we can conclude that $G(z) \in \overline{C}[z_1, \dots, z_n]$, since $G(z) = A(z)/B(z) \in \overline{C}[[z_1, \dots, z_n]]$.

Secondly we show that $Q_k(X) \in \overline{C}[X]$ ($q \leq k \leq p+q-1$). For each k ($q \leq k \leq p+q-1$), let $Q_k(X) = U_k(X)/V_k(X)$, where $U_k(X)$ and $V_k(X)$ are coprime polynomials in $\overline{C}[X]$ with $V_k(0) \neq 0$. Then $U_k(P(\Omega^k z))$ and $V_k(P(\Omega^k z))$ are coprime polynomials in $\overline{C}[z_1, \dots, z_n]$ with $V_k(\mathbf{0}) \neq 0$. By Lemma 11, $V_k(P(\Omega^k z))$ and $V_{k'}(P(\Omega^{k'} z))$ are coprime if $k \neq k'$. Since $G(z) \in \overline{C}[z_1, \dots, z_n]$ and so $G(\Omega^p z) \in \overline{C}[z_1, \dots, z_n]$,

$$\sum_{k=q}^{p+q-1} \frac{U_k(P(\Omega^k z))}{V_k(P(\Omega^k z))} \in \overline{C}[z_1, \dots, z_n]$$

by (7). Hence $V_k(P(\Omega^k z))$ divides $U_k(P(\Omega^k z))$ and so $V_k(P(\Omega^k z)) \in \overline{C}^\times$ for any k ($q \leq k \leq p + q - 1$). Therefore $V_k(X) \in \overline{C}^\times$ and so $Q_k(X) \in \overline{C}[X]$ ($q \leq k \leq p + q - 1$).

Finally we prove that $Q_k(X) \in \overline{C}$ ($q \leq k \leq p + q - 1$), which implies $G(z) \in \overline{C}$ by Lemma 8. To the contrary we assume that $Q_k(X) \notin \overline{C}$ for some k ($q \leq k \leq p + q - 1$). Let g be the number of terms appearing in $G(z)$. Iterating (7), we get

$$G(z) - \alpha^{2g+1}G(\Omega^{(2g+1)^p}z) = \sum_{l=0}^{2g} \alpha^l \sum_{k=q}^{p+q-1} Q_k(P(\Omega^{k+l}z)).$$

Then the number of terms appearing in the right-hand side is at least $2g + 1$, since $(a_{k+n-1} : \dots : a_k) \neq (a_{k'+n-1} : \dots : a_{k'})$ in $P^{n-1}(Q)$ for any distinct nonnegative integers k and k' by Lemma 9 and so the nonconstant terms appearing in the right-hand side never cancel one another. This is a contradiction, since the number of terms appearing in the left-hand side is at most $2g$, and the proof of the theorem is completed. □

Proof of Theorem 2. Letting $G(z) = A(z)/B(z)$, where $A(z)$ and $B(z)$ are coprime polynomials in $\overline{C}[z_1, \dots, z_n]$, and letting for each k ($q \leq k \leq p + q - 1$), $Q_k(X) = U_k(X)/V_k(X)$, where $U_k(X)$ and $V_k(X)$ are coprime polynomials in $\overline{C}[X]$, we have

$$(35) \quad A(z)B(\Omega^p z) \prod_{k=q}^{p+q-1} V_k(P(\Omega^k z)) = A(\Omega^p z)B(z) \prod_{k=q}^{p+q-1} U_k(P(\Omega^k z))$$

by (8). We can put $(A(\Omega^p z), B(\Omega^p z)) = z^I$, where $I \in N_0^n$, by Lemma 6. Let $U_k(X) = c_k \prod_{j=1}^{t_k} (X - \gamma_{kj})^{e_{kj}}$, where c_k is a nonzero element of \overline{C} , $\gamma_{k1}, \dots, \gamma_{kt_k}$ are the distinct roots of $U_k(X)$, and e_{k1}, \dots, e_{kt_k} are positive integers, and let $V_k(X) = d_k \prod_{j=1}^{u_k} (X - \delta_{kj})^{f_{kj}}$, where d_k is a nonzero element of \overline{C} , $\delta_{k1}, \dots, \delta_{ku_k}$ are the distinct roots of $V_k(X)$, and f_{k1}, \dots, f_{ku_k} are positive integers. Then $\gamma_{k1}, \dots, \gamma_{kt_k}, \delta_{k1}, \dots, \delta_{ku_k}$ ($q \leq k \leq p + q - 1$) are nonzero elements of \overline{C} and

$$\begin{aligned} A(\Omega^p z) &| A(z)z^I \prod_{k=q}^{p+q-1} \prod_{j=1}^{u_k} (P(\Omega^k z) - \delta_{kj})^{f_{kj}}, \\ A(z) &| A(\Omega^p z) \prod_{k=q}^{p+q-1} \prod_{j=1}^{t_k} (P(\Omega^k z) - \gamma_{kj})^{e_{kj}}, \\ B(\Omega^p z) &| B(z)z^I \prod_{k=q}^{p+q-1} \prod_{j=1}^{t_k} (P(\Omega^k z) - \gamma_{kj})^{e_{kj}}, \end{aligned}$$

and

$$B(z) \mid B(\Omega^p z) \prod_{k=q}^{p+q-1} \prod_{j=1}^{u_k} (P(\Omega^k z) - \delta_{kj})^{f_{kj}}.$$

Hence by the same way as in the proof of Theorem 1, we see that $A(\Omega^p z)$ divides $A(z)z^I$ and that $B(\Omega^p z)$ divides $B(z)z^I$. Therefore $A(z)$ and $B(z)$ are monomials in z_1, \dots, z_n by Lemmas 1 and 12. Then by (35) and the fact that $U_k(0) \neq 0, V_k(0) \neq 0$ ($q \leq k \leq p+q-1$),

$$\prod_{k=q}^{p+q-1} U_k(P(\Omega^k z)) \Big/ \prod_{k=q}^{p+q-1} V_k(P(\Omega^k z)) \in \overline{C}^\times.$$

Here, $U_k(P(\Omega^k z))$ and $V_{k'}(P(\Omega^{k'} z))$ ($k \neq k'$) are coprime polynomials in $\overline{C}[z_1, \dots, z_n]$ by Lemma 11, and $U_k(P(\Omega^k z)), V_k(P(\Omega^k z))$ are coprime polynomials in $\overline{C}[z_1, \dots, z_n]$ for each k ($q \leq k \leq p+q-1$), since $U_k(X)$ and $V_k(X)$ are coprime in $\overline{C}[X]$. Therefore $U_k(X), V_k(X) \in \overline{C}^\times$ ($q \leq k \leq p+q-1$) and so $Q_k(X) \in \overline{C}^\times$ ($q \leq k \leq p+q-1$). Hence $G(z) \in \overline{C}$ by Lemma 8, and the proof of the theorem is completed. \square

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