Quest Journals
Journal of Research in Applied Mathematics
Volume 11 ~ Issue 12 (December 2025) pp: 120-125
ISSN (Online): 2394-0743 ISSN (Print): 2394-0735
www.questjournals.org

Research Paper

Growth of Special Type Differential Polynomial Generated by Entire and Meromorphic Functions on The Basis of Their (α, β, γ)– Order

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ABSTRACT. In this paper, we establish some results depending on the comparative growth properties of composite transcendental entire or meromorphic functions and some special type of differential polynomials generated by one of the factors on the basis of (α, β, γ)-order and (α, β, γ)-lower order, where α, β, γ are continuous non-negative functions defined on $(-\infty, +\infty)$.

Received 13 Dec., 2025; Revised 24 Dec., 2025; Accepted 26 Dec., 2025

I. Introduction

Throughout this article, we assume that the reader is familiar with the fundamental results and the standard notations of the Nevanlinna theory of meromorphic functions which are available in [4, 5, 8, 7]. We also use the standard notations and definitions of the theory of entire functions which are available in [6] and therefore we do not explain those in details. Let f be an entire function defined in the open complex plane $\mathbb{C}$ and $M_f(r) = \max\{|f(z)| : |z| = r\}$. When f is meromorphic, one may introduce another function $T_f(r)$, known as Nevanlinna's characteristic function of f (see [4, p.4]), playing the same role as $M_f(r)$, which is defined as

$$T_f(r) = N_f(r) + m_f(r),$$

where $m_f(r)$ and $N_f(r)$ are respectively called as the proximity function of f and the counting function of poles of f in $|z| \leq r$. For details about $T_f(r)$, $m_f(r)$ and $N_f(r)$ one may see [4].

If f is entire, then the Nevanlinna's characteristic function $T_f(r)$ of f is defined as

$$\begin{aligned} T_f(r) &= m_f(r) = \frac{1}{2\pi}\int_0^{2\pi} \log^+ \left|f(re^{i\theta})\right| d\theta, \\ \text{where, } \log^+ x &= \max(\log x, 0) \text{ for all } x \geqslant 0. \end{aligned}$$

Further let $n_0, n_1, n_2, ...n_k$ be nonnegative integers. For a transcendental meromorphic function f, we call the expression $M[f] = f^{n_0}(f^{(1)})^{n_1}(f^{(2)})^{n_2}.......(f^{(k)})^{n_k}$ to be a monomial generated by f. The numbers $\gamma_M = n_0 + n_1 + n_2 + ... + n_k$ and

Key words and phrases. Entire function, meromorphic function, growth, special type of differential polynomial, (α, β, γ)-order and (α, β, γ)-lower order.
AMS Subject Classification (2020) : 30D35, 30D30.

$\Gamma_M = n_0 + 2n_1 + 3n_2 + ... + (k+1)n_k$ are called respectively the degree and weight of the monomial. If $M_1[f]$, $M_2[f]$, ..., $M_n[f]$ denote monomials in f, then

$$Q[f] = a_1 M_1[f] + a_2 M_2[f] + ... + a_n M_n[f],$$

where $a_i \neq 0 (i = 1, 2, ..., n)$ is called a differential polynomial generated by f of degree $\gamma_Q = \max\{\gamma_{M_j} : 1 \leq j \leq n\}$ and weight $\Gamma_Q = \max\{\Gamma_{M_J} : 1 \leq j \leq n\}$. Also we call the numbers $\underline{\gamma_Q} = \min_{1 \leq j \leq s} \gamma_{Mj}$ and k (the order of the highest derivative of f) the lower degree and the order of $Q[f]$ respectively. If $\underline{\gamma_Q} = \gamma_Q$, $Q[f]$ is called a homogeneous differential polynomial.

Now, first of all, let L be a class of continuous non-negative on $(-\infty, +\infty)$ function α such that $\alpha(x) = \alpha(x_0) \geq 0$ for $x \leq x_0$ with $\alpha(x) \uparrow +\infty$ as $x_0 \leq x \to +\infty$. We say that $\alpha \in L_1$, if $\alpha \in L$ and $\alpha(a+b) \leq \alpha(a) + \alpha(b) + c$ for all $a, b \geq R_0$ and fixed $c \in (0, +\infty)$. Further we say that $\alpha \in L_2$, if $\alpha \in L$ and $\alpha(x + O(1)) = (1 + o(1))\alpha(x)$ as $x \to +\infty$. Finally, $\alpha \in L_3$ if $\alpha \in L$ and $\alpha(a+b) \leq \alpha(a) + \alpha(b)$ for all $a, b \geq R_0$, i.e., α is subadditive. Clearly $L_3 \subset L_1$.

Particularly, when $\alpha \in L_3$, then one can easily verify that $\alpha(mr) \leq m\alpha(r)$, $m \geq 2$ is an integer. Up to a normalization, subadditivity is implied by concavity. Indeed, if $\alpha(r)$ is concave on $[0, +\infty)$ and satisfies $\alpha(0) \geq 0$, then for $t \in [0, 1]$,

$$\begin{aligned}
\alpha(tx) &= \alpha(tx + (1-t) \cdot 0) \\
&\geq t\alpha(x) + (1-t)\alpha(0) \geq t\alpha(x),
\end{aligned}$$

so that by choosing $t = \frac{a}{a+b}$ or $t = \frac{b}{a+b}$, we obtain

$$\begin{aligned}
\alpha(a+b) &= \frac{a}{a+b}\alpha(a+b) + \frac{b}{a+b}\alpha(a+b) \\
&\leq \alpha\left(\frac{a}{a+b}(a+b)\right) + \alpha\left(\frac{b}{a+b}(a+b)\right) \\
&= \alpha(a) + \alpha(b), \ a, b \geq 0.
\end{aligned}$$

As a non-decreasing, subadditive and unbounded function, $\alpha(r)$ satisfies

$$\alpha(r) \leq \alpha(r + R_0) \leq \alpha(r) + \alpha(R_0)$$

for any $R_0 \geq 0$. This yields that $\alpha(r) \sim \alpha(r + R_0)$ as $r \to +\infty$. Throughout this paper we assume $\alpha \in L_1$, $\beta \in L_2$, $\gamma \in L_3$.

Heittokangas et al. [3] have introduced a new concept of φ-order of entire and meromorphic functions considering φ as subadditive function. For details one may see [3]. Later on Belaïdi et al. [1] have extended the above idea and have introduced the definitions of (α, β, γ)-order and (α, β, γ)-lower order of a meromorphic function f, which are as follows:

Definition 1. [1] *The (α, β, γ)-order denoted by $\rho_{(\alpha,\beta,\gamma)}[f]$ of a meromorphic function f is defined as:*

$$\rho_{(\alpha,\beta,\gamma)}[f] = \limsup_{r \to +\infty} \frac{\alpha(\log(T_f(r)))}{\beta(\log(\gamma(r)))}.$$

Definition 2. [1] *The (α, β, γ)-lower order denoted by $\lambda_{(\alpha,\beta,\gamma)}[f]$ of a meromorphic function f is defined as:*

$$\lambda_{(\alpha,\beta,\gamma)}[f] = \liminf_{r \to +\infty} \frac{\alpha(\log(T_f(r)))}{\beta(\log(\gamma(r)))}.$$

In this paper we aim to establish some results depending on the comparative growth properties of composite transcendental entire or meromorphic functions and some special type of differential polynomials generated by one of the factors on the basis of (α, β, γ)-order and (α, β, γ)-lower order.

2. Lemmas

In this section, we present some lemmas which will be needed in the sequel.

Lemma 1. [2] *Let f be a transcendental meromorphic function and $F = f^n Q[f]$ where $Q[f]$ is a differential polynomial in f, then for any $n \geq 1$*

$$\begin{aligned} T_f(r) &= O\{T_F(r)\} \text{ as } r \to \infty \\ \text{and } T_F(r) &= O\{T_f(r)\} \text{ as } r \to \infty. \end{aligned}$$

Lemma 2. *Let f be a transcendental meromorphic function and $F = f^n Q[f]$ where $Q[f]$ is a differential polynomial in f, then for any $n \geq 1$,*

$$\rho_{(\alpha,\beta,\gamma)}[F] = \rho_{(\alpha,\beta,\gamma)}[f] \text{ and } \lambda_{(\alpha,\beta,\gamma)}[F] = \lambda_{(\alpha,\beta,\gamma)}[f].$$

Proof. Let P and Q be any two constants greater than 1. Now we get from Lemma 1 that for all sufficiently large values of r,

$$T_f(r) < P \cdot T_F(r) \tag{2.1}$$

and

$$T_F(r) < Q \cdot T_f(r). \tag{2.2}$$

Now from (2.1) it follows that for all sufficiently large values of r,

$$\begin{aligned} \log T_f(r) &< \log T_F(r) + \log P, \\ i.e.,\ \alpha(\log T_f(r)) &< \alpha(\log T_F(r)) + O(1), \\ i.e.,\ \frac{\alpha(\log T_f(r))}{\beta(\log \gamma(r))} &< \frac{\alpha(\log T_F(r)) + O(1)}{\beta(\log \gamma(r))}, \end{aligned}$$

$$\begin{aligned} i.e.,\ \limsup_{r\to+\infty} \frac{\alpha(\log T_f(r))}{\beta(\log \gamma(r))} &< \limsup_{r\to+\infty} \frac{\alpha(\log T_F(r))}{\beta(\log \gamma(r))} + \limsup_{r\to+\infty} \frac{O(1)}{\beta(\log \gamma(r))}, \\ i.e.,\ \rho_{(\alpha,\beta,\gamma)}[f] &\leq \rho_{(\alpha,\beta,\gamma)}[F]. \end{aligned} \tag{2.3}$$

Again from (2.2) we obtain that for all sufficiently large values of r,

$$\begin{aligned} \log T_F(r) &< \log T_f(r) + \log Q, \\ i.e.,\ \alpha(\log T_F(r)) &< \alpha(\log T_f(r)) + O(1), \\ i.e.,\ \frac{\alpha(\log T_F(r))}{\beta(\log \gamma(r))} &< \frac{\alpha(\log T_f(r)) + O(1)}{\beta(\log \gamma(r))}, \end{aligned}$$

$$\begin{aligned} i.e.,\ \limsup_{r\to+\infty} \frac{\alpha(\log T_F(r))}{\beta(\log \gamma(r))} &< \limsup_{r\to+\infty} \frac{\alpha(\log T_f(r))}{\beta(\log \gamma(r))} + \limsup_{r\to+\infty} \frac{O(1)}{\beta(\log \gamma(r))}, \\ i.e.,\ \rho_{(\alpha,\beta,\gamma)}[F] &\leq \rho_{(\alpha,\beta,\gamma)}[f]. \end{aligned} \tag{2.4}$$

Therefore from (2.3) and (2.4), we get that

$$\rho_{(\alpha,\beta,\gamma)}[F] = \rho_{(\alpha,\beta,\gamma)}[f].$$

In a similar manner, $\lambda_{(\alpha,\beta,\gamma)}[F] = \lambda_{(\alpha,\beta,\gamma)}[f]$.
Thus the lemma follows. □

3. Main results

In this section, we present the main results of the paper.

Theorem 1. *Let f be a transcendental meromorphic function and g be an entire function such that $0 < \lambda_{(\alpha,\beta,\gamma)}[f] \leq \rho_{(\alpha,\beta,\gamma)}[f] < +\infty$ and $\lambda_{(\alpha,\beta,\gamma)}[f \circ g] = +\infty$. Also let $F = f^n Q[f]$ where $Q[f]$ is a differential polynomial in f for any $n \geq 1$, then*

$$\lim_{r\to+\infty} \frac{\alpha(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} = +\infty.$$

Proof. If possible, let the conclusion of the theorem does not hold. Then we can find a constant $\Delta > 0$ such that for a sequence of values of r tending to infinity

$$\alpha(\log(T_{f\circ g}(r))) \leq \Delta \cdot \alpha(\log(T_F(r))). \tag{3.1}$$

It follows from Lemma 2 and Definition 1 that for all sufficiently large values of r,

$$\alpha(\log(T_F(r))) \leq (\rho_{(\alpha,\beta,\gamma)}[f] + \epsilon)\beta(\log(\gamma(r))). \tag{3.2}$$

From (3.1) and (3.2), for a sequence of values of r tending to $+\infty$, we have

$$\alpha(\log(T_{f\circ g}(r))) \leq \Delta(\rho_{(\alpha,\beta,\gamma)}[f] + \epsilon)\beta(\log(\gamma(r))),$$

$$i.e., \ \frac{\alpha(\log(T_{f\circ g}(r)))}{\beta(\log(\gamma(r)))} \leq \Delta(\rho_{(\alpha,\beta,\gamma)}[f] + \epsilon),$$

$$i.e., \ \liminf_{r\to+\infty} \frac{\alpha(\log(T_{f\circ g}(r)))}{\beta(\log(\gamma(r)))} < +\infty.$$

Hence from Definition 2, we have

$$\lambda_{(\alpha,\beta,\gamma)}[f \circ g] < +\infty.$$

This is a contradiction.

Thus the theorem follows. □

Remark 1. *Theorem 1 is also valid with "limit superior" instead of "limit" if "$\lambda_{(\alpha,\beta,\gamma)}[f\circ g] = +\infty$" is replaced by "$\rho_{(\alpha,\beta,\gamma)}[f\circ g] = +\infty$" and the other conditions remain the same.*

Theorem 2. *Let f be a transcendental meromorphic function and g be an entire function such that $0 < \lambda_{(\alpha,\beta,\gamma)}[f] \leq \rho_{(\alpha,\beta,\gamma)}[f] < +\infty$ and $0 < \lambda_{(\alpha_1,\beta,\gamma)}[f \circ g] \leq \rho_{(\alpha_1,\beta,\gamma)}[f \circ g] < +\infty$. Also let $F = f^n Q[f]$ where $Q[f]$ is a differential polynomial in f for any $n \geq 1$, then*

$$\begin{aligned}
\frac{\lambda_{(\alpha_1,\beta,\gamma)}[f \circ g]}{\rho_{(\alpha,\beta,\gamma)}[f]} &\leq \liminf_{r\to+\infty} \frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \\
&\leq \min\left\{\frac{\lambda_{(\alpha_1,\beta,\gamma)}[f \circ g]}{\lambda_{(\alpha,\beta,\gamma)}[f]}, \frac{\rho_{(\alpha_1,\beta,\gamma)}[f \circ g]}{\rho_{(\alpha,\beta,\gamma)}[f]}\right\} \\
&\leq \max\left\{\frac{\lambda_{(\alpha_1,\beta,\gamma)}[f \circ g]}{\lambda_{(\alpha,\beta,\gamma)}[f]}, \frac{\rho_{(\alpha_1,\beta,\gamma)}[f \circ g]}{\rho_{(\alpha,\beta,\gamma)}[f]}\right\} \\
&\leq \limsup_{r\to+\infty} \frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \leq \frac{\rho_{(\alpha_1,\beta,\gamma)}[f \circ g]}{\lambda_{(\alpha,\beta,\gamma)}[f]}.
\end{aligned}$$

Proof. From Definition 1 and Definition 2, we have that for arbitrary positive ε and for all sufficiently large values of r,

$$\alpha_1(\log(T_{f\circ g}(r))) \geqslant \left(\lambda_{(\alpha_1,\beta,\gamma)}[f \circ g] - \varepsilon\right) \beta(\log(\gamma(r))), \tag{3.3}$$

$$\alpha_1(\log(T_{f\circ g}(r))) \leq \left(\rho_{(\alpha_1,\beta,\gamma)}[f \circ g] + \varepsilon\right) \beta(\log(\gamma(r))). \tag{3.4}$$

Using Lemma 2, we have from Definition 1 and Definition 2 that for arbitrary positive ε and for all sufficiently large values of r,

$$\alpha(\log(T_F(r))) \geqslant \left(\lambda_{(\alpha,\beta,\gamma)}[f] - \varepsilon\right) \beta(\log(\gamma(r))), \tag{3.5}$$

$$\text{and } \alpha(\log(T_F(r))) \leq \left(\rho_{(\alpha,\beta,\gamma)}[f] + \varepsilon\right) \beta(\log(\gamma(r))). \tag{3.6}$$

Again from Definition 1 and Definition 2, we have that for arbitrary positive ε and for a sequence of values of r tending to infinity,

$$\alpha_1(\log(T_{f\circ g}(r))) \leq \left(\lambda_{(\alpha_1,\beta,\gamma)}[f \circ g] + \varepsilon\right) \beta(\log(\gamma(r))), \tag{3.7}$$

$$\alpha_1(\log(T_{f\circ g}(r))) \geqslant \left(\rho_{(\alpha_1,\beta,\gamma)}[f \circ g] - \varepsilon\right) \beta(\log(\gamma(r))). \tag{3.8}$$

Also, using Lemma 2, we get from Definition 1 and Definition 2 that for arbitrary positive ε and for a sequence of values of r tending to infinity,

$$\alpha(\log(T_F(r))) \leq \left(\lambda_{(\alpha,\beta,\gamma)}[f] + \varepsilon\right) \beta(\log(\gamma(r))), \tag{3.9}$$

$$\text{and } \alpha(\log(T_F(r))) \geqslant \left(\rho_{(\alpha,\beta,\gamma)}[f] - \varepsilon\right) \beta(\log(\gamma(r))). \tag{3.10}$$

Now from (3.3) and (3.6) it follows that for all sufficiently large values of r,

$$\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \geqslant \frac{\lambda_{(\alpha_1,\beta,\gamma)}[f \circ g] - \varepsilon}{\rho_{(\alpha,\beta,\gamma)}[f] + \varepsilon}.$$

As $\varepsilon\,(> 0)$ is arbitrary, we obtain that

$$\liminf_{r\to+\infty} \frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \geqslant \frac{\lambda_{(\alpha_1,\beta,\gamma)}[f \circ g]}{\rho_{(\alpha,\beta,\gamma)}[f]}. \tag{3.11}$$

Combining (3.5) and (3.7), we have that for a sequence of values of r tending to infinity,

$$\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \le \frac{\lambda_{(\alpha_1,\beta,\gamma)}[f\circ g]+\varepsilon}{\lambda_{(\alpha,\beta,\gamma)}[f]-\varepsilon}.$$

Since $\varepsilon\,(>0)$ is arbitrary, it follows that

$$\liminf_{r\to+\infty}\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \le \frac{\lambda_{(\alpha_1,\beta,\gamma)}[f\circ g]}{\lambda_{(\alpha,\beta,\gamma)}[f]}. \tag{3.12}$$

Again from (3.3) and (3.9), for a sequence of values of r tending to infinity, we get

$$\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \ge \frac{\lambda_{(\alpha_1,\beta,\gamma)}[f\circ g]-\varepsilon}{\lambda_{(\alpha,\beta,\gamma)}[f]+\varepsilon}.$$

As $\varepsilon\,(>0)$ is arbitrary, we get from above that

$$\limsup_{r\to+\infty}\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \ge \frac{\lambda_{(\alpha_1,\beta,\gamma)}[f\circ g]}{\lambda_{(\alpha,\beta,\gamma)}[f]}. \tag{3.13}$$

Also, it follows from (3.4) and (3.5) that for all sufficiently large values of r,

$$\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \le \frac{\rho_{(\alpha_1,\beta,\gamma)}[f\circ g]+\varepsilon}{\lambda_{(\alpha,\beta,\gamma)}[f]-\varepsilon}.$$

Since $\varepsilon\,(>0)$ is arbitrary, we obtain that

$$\limsup_{r\to+\infty}\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \le \frac{\rho_{(\alpha_1,\beta,\gamma)}[f\circ g]}{\lambda_{(\alpha,\beta,\gamma)}[f]}. \tag{3.14}$$

Now from (3.4) and (3.10), it follows that for a sequence of values of r tending to infinity,

$$\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \le \frac{\rho_{(\alpha_1,\beta,\gamma)}[f\circ g]+\varepsilon}{\rho_{(\alpha,\beta,\gamma)}[f]-\varepsilon}.$$

As $\varepsilon\,(>0)$ is arbitrary, we obtain that

$$\liminf_{r\to+\infty}\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \le \frac{\rho_{(\alpha_1,\beta,\gamma)}[f\circ g]}{\rho_{(\alpha,\beta,\gamma)}[f]}. \tag{3.15}$$

Combining (3.6) and (3.8), we get that for a sequence of values of r tending to infinity,

$$\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \geqslant \frac{\rho_{(\alpha_1,\beta,\gamma)}[f\circ g]-\varepsilon}{\rho_{(\alpha,\beta,\gamma)}[f]+\varepsilon}.$$

Since $\varepsilon\,(>0)$ is arbitrary, it follows that

$$\limsup_{r\to+\infty}\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_F(r)))} \geqslant \frac{\rho_{(\alpha_1,\beta,\gamma)}[f\circ g]}{\rho_{(\alpha,\beta,\gamma)}[f]}. \tag{3.16}$$

Thus the theorem follows from (3.11), (3.12), (3.13), (3.14), (3.15) and (3.16). □

The following theorem can be carried out in the line of Theorem 2 and therefore we omit its proof.

Theorem 3. *Let f be a transcendental meromorphic function and g be a transcendental entire function such that $0<\lambda_{(\alpha,\beta,\gamma)}[g]\le\rho_{(\alpha,\beta,\gamma)}[g]<+\infty$ and $0<\lambda_{(\alpha_1,\beta,\gamma)}[f\circ g]\le\rho_{(\alpha_1,\beta,\gamma)}[f\circ g]<+\infty$. Also let $G=g^mQ[g]$ where $Q[g]$ is a differential polynomial in g. Then for any $m\ge 1$,*

$$\begin{aligned}\frac{\lambda_{(\alpha_1,\beta,\gamma)}[f\circ g]}{\rho_{(\alpha,\beta,\gamma)}[g]} &\le \liminf_{r\to+\infty}\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_G(r)))}\\ &\le \min\left\{\frac{\lambda_{(\alpha_1,\beta,\gamma)}[f\circ g]}{\lambda_{(\alpha,\beta,\gamma)}[g]},\frac{\rho_{(\alpha_1,\beta,\gamma)}[f\circ g]}{\rho_{(\alpha,\beta,\gamma)}[g]}\right\}\\ &\le \max\left\{\frac{\lambda_{(\alpha_1,\beta,\gamma)}[f\circ g]}{\lambda_{(\alpha,\beta,\gamma)}[g]},\frac{\rho_{(\alpha_1,\beta,\gamma)}[f\circ g]}{\rho_{(\alpha,\beta,\gamma)}[g]}\right\}\\ &\le \limsup_{r\to+\infty}\frac{\alpha_1(\log(T_{f\circ g}(r)))}{\alpha(\log(T_G(r)))} \le \frac{\rho_{(\alpha_1,\beta,\gamma)}[f\circ g]}{\lambda_{(\alpha,\beta,\gamma)}[g]}.\end{aligned}$$

Acknowledgement

The authors are very much thankful to the reviewer for his/her valuable suggestions to bring the paper in its present form.

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