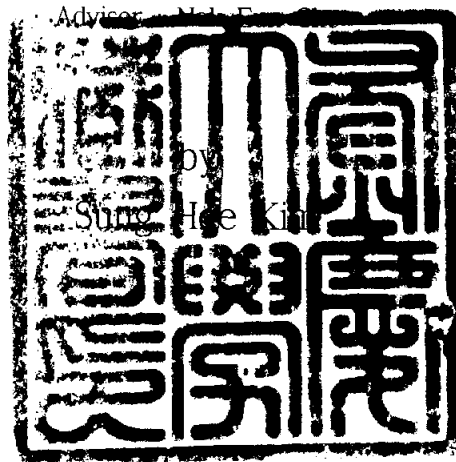


On the Fekete-Szegő problem for certain analytic functions

어떤 해석적 함수들에 대한 Fekete-Szegő 문제



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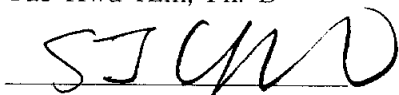
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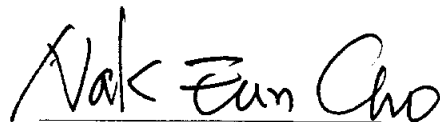
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어떤 해석적 함수들에 대한 Fekete-Szegő 문제

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요 약

기하함수이론은 지금까지 많은 학자들에 의하여 다양하게 연구되어 왔다. 단엽함수들의 계수문제와 관련하여 1933년 Fekete-Szegő는 단위원 내부에서 정의된 단엽함수

$f(z) = z + \sum_{n=2}^{\infty} a_n z^n$ 에 대한 sharp한 계수부등식

$$|a_3 - \mu a_2^2| \leq 1 + 2e^{-2\mu(1-\mu)} \quad (\mu \in [0, 1])$$

을 증명하였다. Fekete와 Szegő 이후 여러학자들에 의하여 이문제는 집중적으로 연구되었으며 특히, Keopf는 위 문제가 close-to-convex함수들에 대하여는 아주 다른 성질을 갖는다는 것을 밝혔다. 최근 Fekete-Szegő문제에 대한 연구는 다양한 단엽함수들과 복소변수 μ 에 대하여 Thoms, London, Pfluger 등의 학자들에 의하여 활발하게 연구가 진행되고 있다.

본 논문에서는 위수 β 의 강 α -대수적 볼록함수들과 위수 β 의 강 α -대수적 준볼록함수들의 개념을 소개하고, 이 함수들에 대하여 sharp한 Fekete-Szegő 부등식을 증명하였으며, Abdel-Gawad와 Thomas, Keogh와 Merkes 및 London에 의하여 연구된 결과들을 확장·발전시켰다.

I. Introduction

Let $\mathcal{S}$ denote the class of analytic functions f of the form

$$f(z) = z + \sum_{n=2}^{\infty} a_n z^n \quad (1.1)$$

which are univalent in the open unit disk $\mathcal{U} = \{z : |z| < 1\}$. A classical theorem of Fekete and Szegő [8] states that for $f \in \mathcal{S}$ given by (1.1),

$$|a_3 - \mu a_2^2| \leq \begin{cases} 3 - 4\mu & \text{if } \mu \leq 0, \\ 1 + 2e^{-2\mu/(1-\mu)} & \text{if } 0 \leq \mu \leq 1, \\ 4\mu - 3 & \text{if } \mu \geq 1. \end{cases}$$

This inequality is sharp in the sense that for each μ there exists a function in $\mathcal{S}$ such that equality holds. Recently, Pfluger [17,18] has considered the problem when μ is complex. In the case of $\mathcal{C}$, $\mathcal{S}^*$ and $\mathcal{K}$, the subclasses of convex, starlike and close-to-convex functions, respectively, the above inequality can be improved [10,11]. Also, Darus and Thomas [5] studied the class $\mathcal{M}^\alpha$ of α -logarithmic convex functions and they also have solved the Fekete-Szegő problem for the class $\mathcal{M}^\alpha$. Furthermore, London [14] have extended the results of Abdel-Gawad and Thomas [1], Keogh and Merkes [10] and Koepf [11,12] to the class $\mathcal{K}(\beta)$ of strongly close-to-convex functions of order β . Now we introduce new classes which incorporate well-known classes of univalent functions.

Definition 1.1. A function $f \in \mathcal{S}$ given by (1.1) is said to be strongly α -logarithmic convex of order β if

Typeset by $\mathcal{A}\mathcal{M}\mathcal{S}$ - $\mathcal{T}\mathcal{E}\mathcal{X}$

$$\left| \arg \left\{ \left(\frac{zf'(z)}{f(z)} \right)^{1-\alpha} \left(\frac{(zf'(z))'}{f'(z)} \right)^\alpha \right\} \right| \leq \frac{\pi}{2} \beta \quad (\alpha \geq 0; 0 < \beta \leq 1; z \in \mathcal{U}). \quad (1.2)$$

Denote by $\mathcal{M}^\alpha(\beta)$ the class of strongly α -logarithmic convex functions of order β . The class $\mathcal{M}^\alpha(\beta)$ was introduced by Chiang [4]. In particular, the classes $\mathcal{M}^\alpha(1) = \mathcal{M}^\alpha$ and $\mathcal{M}^0(\beta)$ have been extensively studied by Lewandowski, Miller and Zlotkiewicz [13] and Bramnan and Kirwan [2] (also, see [7,20]), respectively.

Definition 1.2. A function $f \in \mathcal{S}$ given by (1.1) is said to be strongly α -logarithmic quasi-convex of order β if there exists a function $g \in \mathcal{C}$ such that

$$\left| \arg \left\{ \left(\frac{f'(z)}{g'(z)} \right)^{1-\alpha} \left(\frac{(zf'(z))'}{g'(z)} \right)^\alpha \right\} \right| \leq \frac{\pi}{2} \beta \quad (\alpha, \beta \geq 0; z \in \mathcal{U}). \quad (1.3)$$

We denote by $\mathcal{Q}^\alpha(\beta)$ the class of strongly α -logarithmic quasi-convex functions of order β . Clearly, $\mathcal{Q}^0(1)$ and $\mathcal{Q}^1(1)$ are the classes of close-to-convex functions and quasi-convex functions introduced by Kaplan [9] and Noor [15] (also, see [16]), respectively. Also we note that $\mathcal{Q}^0(\beta) = \mathcal{K}(\beta)$.

In the present paper, we derive sharp Fekete-Szegő inequalities for functions belonging to the classes $\mathcal{M}^\alpha(\beta)$ and $\mathcal{Q}^\alpha(\beta)$, which imply the results obtained by Abdel-Gawad and Thomas [1], Darus and Thomas [5], Keogh and Merkes [10], Koepf [11,12], and London [14].

II. Main Result

To prove our main results, we need the following.

Lemma 2.1. *Let p be analytic in $\mathcal{U}$ and satisfy $\operatorname{Re} \{p(z)\} > 0$ for $z \in \mathcal{U}$, with $p(z) = 1 + p_1z + p_2z^2 + \dots$. Then*

$$|p_n| \leq 2 \quad (n \geq 1) \quad (2.1)$$

and

$$\left| p_2 - \frac{p_1^2}{2} \right| \leq 2 - \frac{|p_1|^2}{2}. \quad (2.2)$$

The inequality (2.1) was first proved by Carathéodory [3](also, see Duren [6, p. 41]) and the inequality (2.2) can be found in [19, p.166].

With the help of Lemma 2.1, we now derive

Theorem 2.1. *Let $f \in \mathcal{M}^\alpha(\beta)$ and be given by (1.1). Then for complex number μ ,*

$$|a_3 - \mu a_2^2| \leq \frac{\beta}{1 + 2\alpha} \max \left\{ 1, \frac{|3(1 + 3\alpha) - 4\mu(1 + 2\alpha)|\beta}{(1 + \alpha)^2} \right\}.$$

For each μ , there is a function in $\mathcal{M}^\alpha(\beta)$ such that equality holds.

Proof. From (1.2), we can write

$$\left(\frac{zf'(z)}{f(z)}\right)^{1-\alpha} \left(\frac{(zf'(z))'}{f'(z)}\right)^\alpha = p^\beta(z),$$

where p is given by Lemma 2.1. Equating coefficients, we obtain

$$a_2 = \frac{\beta}{1+\alpha} p_1 \quad (2.3)$$

and

$$a_3 = \frac{1}{4(1+2\alpha)} \left(\beta(\beta-1)p_1^2 + 2\beta p_2 - (\alpha^2 - 7\alpha - 2) \left(\frac{\beta p_1}{1+\alpha} \right)^2 \right).$$

Then we have

$$a_3 - \mu a_2^2 = \frac{\beta}{2(1+2\alpha)} \left(p_2 - \frac{p_1^2}{2} \right) + \frac{(3+9\alpha-4\mu(1+2\alpha))\beta^2 p_1^2}{4(1+2\alpha)(1+\alpha)^2}. \quad (2.4)$$

Hence (2.4) and Lemma 2.1 give

$$\begin{aligned} |a_3 - \mu a_2^2| &\leq \frac{\beta}{2(1+2\alpha)} \left(2 - \frac{|p_1|^2}{2} \right) + \frac{|3+9\alpha-4\mu(1+2\alpha)|\beta^2 |p_1|^2}{4(1+2\alpha)(1+\alpha)^2} \\ &\leq \frac{\beta}{1+2\alpha} + \frac{\{|3+9\alpha-4\mu(1+2\alpha)|\beta^2 - (1+\alpha)^2\beta\} |p_1|^2}{4(1+2\alpha)(1+\alpha)^2}. \end{aligned}$$

Therefore, by using $|p_1| \leq 2$, we have

$$|a_3 - \mu a_2^2| \leq \begin{cases} \frac{\beta}{1+2\alpha}, & \text{if } k(\alpha) \leq \frac{(1+\alpha)^2}{\beta}, \\ \frac{|3+9\alpha-4\mu(1+2\alpha)|\beta^2}{(1+2\alpha)(1+\alpha)^2}, & \text{if } k(\alpha) \geq \frac{(1+\alpha)^2}{\beta}, \end{cases}$$

where

$$k(\alpha) = |3(1 + 3\alpha) - 4\mu(1 + 2\alpha)|.$$

Equality is attained for functions in $\mathcal{M}^\alpha(\beta)$, respectively, given by

$$\left(\frac{zf'(z)}{f(z)}\right)^{1-\alpha} \left(\frac{(zf'(z))'}{f'(z)}\right)^\alpha = \left(\frac{1+z^2}{1-z^2}\right)^\beta \quad (2.5)$$

and

$$\left(\frac{zf'(z)}{f(z)}\right)^{1-\alpha} \left(\frac{(zf'(z))'}{f'(z)}\right)^\alpha = \left(\frac{1+z}{1-z}\right)^\beta. \quad (2.6)$$

Remark 2.1. It follows at once from (2.3) that $|a_2| \leq 2\beta/(1 + \alpha)$ and Theorem 2.1 gives

$$|a_3| \leq \begin{cases} \frac{\beta}{1+2\alpha}, & \text{if } (1 + \alpha)^2 \geq 3(1 + 3\alpha)\beta, \\ \frac{3(1+3\alpha)\beta^2}{(1+2\alpha)(1+\alpha)^2}, & \text{if } (1 + \alpha)^2 \leq 3(1 + 3\alpha)\beta, \end{cases}$$

The inequality for $|a_2|$ is sharp when f is defined by (2.6) and the inequalities for $|a_3|$ are sharp when f is defined by (2.5) and (2.6), respectively.

Next, we consider the real number μ as follows.

Theorem 2.2. *Let $f \in \mathcal{M}^\alpha(\beta)$ and be given by (1.1). Then for real number μ ,*

$$|a_3 - \mu a_2^2| \leq \begin{cases} \frac{(3(1+3\alpha)-4(1+2\alpha)\mu)\beta^2}{(1+2\alpha)(1+\alpha)^2}, & \text{if } \mu \leq \frac{3(1+3\alpha)\beta-(1+\alpha)^2}{4(1+2\alpha)\beta}, \\ \frac{\beta}{1+2\alpha}, & \text{if } \frac{3(1+3\alpha)\beta-(1+\alpha)^2}{4(1+2\alpha)\beta} \leq \mu \leq \frac{3(1+3\alpha)\beta+(1+\alpha)^2}{4(1+2\alpha)\beta}, \\ \frac{(4(1+2\alpha)\mu-3(1+3\alpha))\beta^2}{(1+2\alpha)(1+\alpha)^2}, & \text{if } \mu \geq \frac{3(1+3\alpha)\beta+(1+\alpha)^2}{4(1+2\alpha)\beta}. \end{cases}$$

For each μ , there is a function in $\mathcal{M}^\alpha(\beta)$ such that equality holds in all cases.

Proof. We consider two cases. At first, we suppose that $\mu \leq 3(1+3\alpha)/(4(1+2\alpha))$. Then (2.3) and Lemma 2.1 give

$$\begin{aligned} |a_3 - \mu a_2^2| &\leq \frac{\beta}{2(1+2\alpha)} \left(2 - \frac{|p_1|^2}{2} \right) + \frac{(3+9\alpha-4\mu(1+2\alpha))\beta^2|p_1|^2}{4(1+2\alpha)(1+\alpha)^2} \\ &\leq \frac{\beta}{1+2\alpha} + \frac{((3+9\alpha-4\mu(1+2\alpha))\beta^2 - (1+\alpha)^2\beta)|p_1|^2}{4(1+2\alpha)(1+\alpha)^2}. \end{aligned}$$

So, by using the fact that $|p_1| \leq 2$, we obtain

$$|a_3 - \mu a_2^2| \leq \begin{cases} \frac{(3(1+3\alpha)-4(1+2\alpha)\mu)\beta^2}{(1+2\alpha)(1+\alpha)^2}, & \text{if } \mu \leq \frac{3(1+3\alpha)\beta-(1+\alpha)^2}{4(1+2\alpha)\beta}, \\ \frac{\beta}{1+2\alpha}, & \text{if } \frac{3(1+3\alpha)\beta-(1+\alpha)^2}{4(1+2\alpha)\beta} \leq \mu \leq \frac{3(1+3\alpha)\beta+(1+\alpha)^2}{4(1+2\alpha)\beta}, \end{cases}$$

Equality is attained by choosing $p_1 = p_2 = 2$ and $p_1 = 0, p_2 = 2$, respectively, in (2.3).

Next, we suppose that $\mu \geq 3(1+3\alpha)/(4(1+2\alpha))$. In this case, it follows again from (2.3) and Lemma 2.1 that

$$\begin{aligned} |a_3 - \mu a_2^2| &\leq \frac{\beta}{2(1+2\alpha)} \left(2 - \frac{|p_1|^2}{2} \right) + \frac{(4\mu(1+2\alpha) - (3+9\alpha))\beta^2|p_1|^2}{4(1+2\alpha)(1+\alpha)^2} \\ &\leq \frac{\beta}{1+2\alpha} + \frac{((4\mu(1+2\alpha) - (3+9\alpha))\beta^2 - \beta(1+\alpha)^2)|p_1|^2}{4(1+2\alpha)(1+\alpha)^2}, \end{aligned}$$

and so, as in the first case, we have

$$|a_3 - \mu a_2^2| \leq \begin{cases} \frac{\beta}{1+2\alpha}, & \text{if } \frac{3(1+3\alpha)}{4(1+2\alpha)} \leq \mu \leq \frac{3(1+3\alpha)\beta+(1+\alpha)^2}{4(1+2\alpha)\beta}, \\ \frac{(4(1+2\alpha)\mu-3(1+3\alpha))\beta^2}{(1+2\alpha)(1+\alpha)^2}, & \text{if } \mu \geq \frac{3(1+3\alpha)\beta+(1+\alpha)^2}{4(1+2\alpha)\beta}. \end{cases}$$

The results are sharp by choosing $p_1 = 0$, $p_2 = 2$ and $p_1 = 2i$, $p_2 = -2$, respectively, in (2.3).

Remark 2.2. If we take $\beta = 1$ in Theorem 2.1 and Theorem 2.2, then we obtain the results by Darus and Thomas [5].

Finally, we prove

Theorem 2.3. Let $f \in Q^\alpha(\beta)$ and be given by (1.1). Then for $\alpha \geq 0$ and $\beta \geq 0$, we have

$$3(2\alpha+1)|a_3 - \mu a_2^2| \leq \begin{cases} 1 + \frac{(1+\beta)^2(2(3\alpha+1)-3(2\alpha+1)\mu)}{(\alpha+1)^2}, & \text{if } \mu \leq \frac{2\alpha(1-\alpha)+2\beta(3\alpha+1)}{3(2\alpha+1)(1+\beta)}, \\ 1 + 2\beta + \frac{2(2(3\alpha+1)-3(2\alpha+1)\mu)}{2(\alpha+1)^2-\beta(2(3\alpha+1)-3(2\alpha+1)\mu)}, & \text{if } \frac{2\alpha(1-\alpha)+2\beta(3\alpha+1)}{3(2\alpha+1)(1+\beta)} \leq \mu \leq \frac{2(3\alpha+1)}{3(2\alpha+1)}, \\ 1 + 2\beta, & \text{if } \frac{2(3\alpha+1)}{3(2\alpha+1)} \leq \mu \leq \frac{2(\alpha+1)^2+2(3\alpha+1)(1+\beta)}{3(2\alpha+1)(1+\beta)}, \\ -1 + \frac{(1+\beta)^2(3(2\alpha+1)\mu-2(3\alpha+1))}{(\alpha+1)^2}, & \text{if } \mu \geq \frac{2(\alpha+1)^2+2(3\alpha+1)(1+\beta)}{3(2\alpha+1)(1+\beta)}. \end{cases}$$

For each μ , there is a function in $Q^\alpha(\beta)$ such that equality holds in all cases.

Proof. Let $f \in Q^\alpha(\beta)$. Then it follows from (1.2) that we may write

$$\left(\frac{f'(z)}{g'(z)}\right)^{1-\alpha} \left(\frac{(zf'(z))'}{g'(z)}\right)^\alpha = p^\beta(z), \quad (2.7)$$

where g is convex and p has positive real part. Let $g(z) = z + b_2 z^2 + b_3 z^3 + \dots$ and let p be given in the Lemma above. Then by comparing the coefficients of both sides of (2.7), we obtain

$$2(\alpha + 1)a_2 = \beta p_1 + 2b_2$$

and

$$\begin{aligned} 3(2\alpha + 1)a_3 &= 3b_3 + \frac{2\alpha(1 - \alpha)}{(\alpha + 1)^2} b_2^2 + \beta \left(p_2 - \frac{1}{2} p_1^2 \right) \\ &\quad + \frac{\beta^2(3\alpha + 1)}{2(\alpha + 1)^2} p_1^2 + \frac{2\beta(3\alpha + 1)}{(\alpha + 1)^2} p_1 b_2. \end{aligned}$$

So, with

$$x = \frac{2(3\alpha + 1) - 3(2\alpha + 1)\mu}{(\alpha + 1)^2},$$

we have

$$\begin{aligned} 3(2\alpha + 1)(a_3 - \mu a_2^2) &= 3 \left(b_3 + \frac{1}{3}(x - 2)b_2^2 \right) \\ &\quad + \beta \left(p_2 + \frac{1}{4}(\beta x - 2)p_1^2 \right) + \beta x p_1 b_2. \end{aligned} \tag{2.8}$$

Since rotations of f also belong to $\mathcal{Q}^\alpha(\beta)$, without loss of generality, we may assume that $a_3 - \mu a_2^2$ is positive. Thus we now estimate $\operatorname{Re} (a_3 - \mu a_2^2)$.

Since $g \in \mathcal{C}$, there exists $h(z) = 1 + k_1 z + k_2 z^2 + \dots$ ($|z| < 1$) with positive real part, such that $g'(z) + z g''(z) = g'(z) h(z)$. Hence, by equating coefficients, we get that $b_2 = k_1/2$ and $b_3 = (k_2 + k_1^2)/6$. So, by Lemma 2.1,

$$\begin{aligned}
3\operatorname{Re}\left(b_3 + \frac{1}{3}(x-2)b_2^2\right) &= \frac{1}{2}\operatorname{Re}\left(k_2 - \frac{1}{2}k_1^2\right) + \frac{1}{4}(x+1)\operatorname{Re}k_1^2 \\
&\leq 1 - \rho^2 + (x+1)\rho^2 \cos 2\phi,
\end{aligned} \tag{2.9}$$

where $b_2 = k_1/2 = \rho e^{i\phi}$ for some ρ ($0 \leq \rho \leq 1$). We also have

$$\begin{aligned}
\beta\operatorname{Re}\left(p_2 + \frac{1}{4}(\beta x - 2)p_1^2\right) &= \beta\operatorname{Re}\left(p_2 - \frac{1}{2}p_1^2\right) + \frac{1}{4}\beta^2 x \operatorname{Re}p_1^2 \\
&\leq 2\beta(1 - r^2) + \beta^2 x r^2 \cos 2\theta,
\end{aligned} \tag{2.10}$$

where $p_1 = 2re^{i\theta}$ for some r ($0 \leq r \leq 1$). From (2.8-10), we obtain

$$\begin{aligned}
3\operatorname{Re}(2\alpha + 1)(a_3 - \mu a_2^2) &\leq 1 - \rho^2 + (x+1)\rho^2 \cos 2\phi \\
&\quad + 2\beta(1 - r^2) + \beta^2 x r^2 \cos 2\theta + 2\beta x r \rho \cos(\theta + \phi),
\end{aligned} \tag{2.11}$$

and we now proceed to maximize the right-hand of (2.11). This function will be denoted by $\psi(x)$ whenever all the parameters except x are held constant.

We consider first the case

$$\frac{2\alpha(1 - \alpha) + 2\beta(3\alpha + 1)}{3(2\alpha + 1)(1 + \beta)} \leq \mu \leq \frac{2(3\alpha + 1)}{3(2\alpha + 1)},$$

so that $0 \leq x \leq 2/(1 + \beta)$. Since the expression $-2t^2 + t^2\beta x \cos 2\theta + 2xt$ is the largest when $t = x/(2 - \beta x \cos 2\theta)$, we have

$$-2t^2 + t^2\beta x \cos 2\theta + 2xt \leq \frac{x^2}{2 - \beta x \cos 2\theta} \leq \frac{x^2}{2 - \beta x}.$$

Thus

$$\begin{aligned}\psi(x) &\leq x + 1 + \beta \left(2 + \frac{x^2}{2 - \beta x} \right) \\ &= 1 + 2\beta + \frac{2\{2(3\alpha + 1) - 3(2\alpha + 1)\mu\}}{2(\alpha + 1)^2 - \beta\{2(3\alpha + 1) - 3(2\alpha + 1)\mu\}}\end{aligned}$$

and with (2.11) this establishes the second inequality in the theorem. Equality occurs only if

$$p_1 = \frac{2x}{2 - \beta x} = \frac{2\{2(3\alpha + 1) - 3(2\alpha + 1)\mu\}}{2(\alpha + 1)^2 - \beta\{2(3\alpha + 1) - 3(2\alpha + 1)\mu\}}, \quad p_2 = 2, \quad b_2 = b_3 = 1,$$

and the corresponding function f is defined by

$$(f'(z))^{1-\alpha}((zf'(z))')^\alpha = \frac{1}{(1-z)^2} \left(\lambda \frac{1+z}{1-z} + (1-\lambda) \frac{1-z}{1+z} \right)^\beta$$

where

$$\lambda = \frac{2(\alpha + 1)^2 + (1 - \beta)(2(3\alpha + 1) - 3(2\alpha + 1)\mu)}{4(\alpha + 1)^2 - 2\beta(2(3\alpha + 1) - 3(2\alpha + 1)\mu)}.$$

We now prove the first inequality. Let

$$\mu \leq \frac{2\alpha(1 - \alpha) + 2\beta(3\alpha + 1)}{3(2\alpha + 1)(1 + \beta)},$$

so that $x \geq 2/(1 + \beta)$. With $x_0 = 2/(1 + \beta)$, we have

$$\begin{aligned}
\psi(x) &= \psi(x_0) + (x - x_0)(\rho^2 \cos 2\phi + \beta^2 r^2 \cos 2\theta + 2\beta pr \cos(\theta + \phi)) \\
&\leq \psi(x_0) + (x - x_0)(1 + \beta)^2 \\
&\leq 1 + \frac{(1 + \beta)^2 \{2(3\alpha + 1) - 3(2\alpha + 1)\mu\}}{(\alpha + 1)^2}
\end{aligned}$$

as required. Equality occurs only if $p_1 = p_2 = 2$, $b_2 = b_3 = 1$, and the corresponding function f is defined by

$$(f'(z))^{1-\alpha}((zf'(z))')^\alpha = \frac{1}{(1-z)^2} \left(\frac{1+z}{1-z} \right)^\beta$$

Let $x_1 = -2/(1+\beta)$. We shall find that $\psi(x_1) \leq 1 + 2\beta$, and the remaining inequalities follow easily from this one. By an argument similar to the one above, we obtain

$$\begin{aligned}
\psi(x) &\leq \psi(x_1) + |x - x_1|(1 + \beta)^2 \\
&\leq -1 + \frac{(1 + \beta)^2 \{3(2\alpha + 1)\mu - 2(3\alpha + 1)\}}{(\alpha + 1)^2}.
\end{aligned}$$

if $x \leq x_1$, that is,

$$\mu \geq \frac{2(\alpha + 1)^2 + 2(3\alpha + 1)(1 + \beta)}{3(2\alpha + 1)(1 + \beta)}.$$

Equality occurs only if $p_1 = 2i$, $b_2 = i$, $p_2 = -2$, $b_3 = -1$, and the corresponding function f is defined by

$$(f'(z))^{1-\alpha}((zf'(z))')^\alpha = \frac{1}{(1-iz)^2} \left(\frac{1+iz}{1-iz} \right)^\beta, \quad f(0) = 0.$$

Also, for $0 \leq \lambda \leq 1$, we note that

$$\begin{aligned}\psi(\lambda x_1) &= \lambda\psi(x_1) + (1 - \lambda)\psi(0) \\ &\leq \lambda(1 + 2\beta) + (1 - \lambda)(1 + 2\beta) = 1 + 2\beta,\end{aligned}$$

so $\psi(x) \leq 1 + 2\beta$ for $x_1 \leq x \leq 0$, that is,

$$\frac{2(3\alpha + 1)}{3(2\alpha + 1)} \leq \mu \leq \frac{2(\alpha + 1)^2 + 2(3\alpha + 1)(1 + \beta)}{3(2\alpha + 1)(1 + \beta)}.$$

Equality occurs only if $p_1 = b_2 = 0$, $p_2 = 2$, $b_3 = 1/3$, and the corresponding function f is defined by

$$(f'(z))^{1-\alpha}((zf'(z)))^\alpha = \frac{1}{1-z^2} \left(\frac{1+z^2}{1-z^2} \right)^\beta = \frac{(1+z^2)^\beta}{(1-z^2)^{1+\beta}}.$$

We now show that $\psi(x_1) \leq 1 + 2\beta$. Since

$$\begin{aligned}&(-2 + \beta x_1 \cos 2\theta)t^2 + 2x_1 t \rho \cos(\theta + \phi) \\ &= (-2 + \beta x_1 \cos 2\theta) \left\{ t + \frac{x_1 \rho \cos(\theta + \phi)}{-2 + \beta x_1 \cos 2\theta} \right\}^2 + \frac{x_1^2 \rho^2 \cos^2(\theta + \phi)}{2 - \beta x_1 \cos 2\theta}\end{aligned}$$

for all real t and

$$2 - \beta x_1 \cos 2\theta = 2 + \frac{2\beta}{1 + \beta} \cos 2\theta \geq 2 - \frac{2\beta}{1 + \beta} \geq 0,$$

we have

$$\psi(x_1) - (1 + 2\beta) \leq \rho^2 \left(-1 + (x_1 + 1) \cos 2\phi + \frac{\beta x_1^2 (1 + \cos 2(\theta + \phi))}{2(2 - \beta x_1 \cos 2\theta)} \right).$$

Thus we consider the inequality

$$\beta x_1^2(1 + \cos 2(\theta + \phi)) + 2(2 - \beta x_1 \cos 2\theta)(-1 + (x_1 + 1) \cos 2\phi) \leq 0.$$

After some simplifications, this becomes

$$4(\beta^2(\cos 2\phi + 1)(\cos 2\phi - 1) - \beta(1 + \cos 2\theta + \sin 2\theta \sin 2\phi) - 1 - \cos 2\phi) \leq 0,$$

which is true if

$$2\beta^2 \cos^2 \theta \sin^2 \phi + 2\beta \cos \theta \sin \theta \cos \phi \sin \phi + \cos^2 \phi \geq 0. \quad (2.12)$$

Now, for all real t ,

$$2t^2 + 2t \sin \theta \cos \phi + \cos^2 \phi \geq 0,$$

so, by taking $t = \beta \cos \theta \sin \phi$, we obtain (2.12). This completes the proof of the theorem.

Remark. Letting $\alpha = 0$ in Theorem 2.3, we have the corresponding result obtained by London [14], which extend the earlier results by several authors [1,5,10-12].

For $\alpha = 1$ in Theorem 2.3, we have the following

Corollary 2.1. *Let $f \in \mathcal{Q}^1(\beta)$ and be given by (1.1). Then for $\beta \geq 0$, we have*

$$9 |a_3 - \mu a_2^2| \leq \begin{cases} 1 + \frac{(1+\beta)^2(8-9\mu)}{4} & \text{if } \mu \leq \frac{8\beta}{9(1+\beta)}, \\ 1 + 2\beta + \frac{2(8-9\mu)}{8-\beta(8-9\mu)} & \text{if } \frac{8\beta}{9(1+\beta)} \leq \mu \leq \frac{8}{9}, \\ 1 + 2\beta & \text{if } \frac{8}{9} \leq \mu \leq \frac{8(2+\beta)}{9(1+\beta)}, \\ -1 + \frac{(1+\beta)^2(9\mu-8)}{4} & \text{if } \mu \geq \frac{8(2+\beta)}{9(1+\beta)}. \end{cases}$$

For each μ , there is a function in $\mathcal{Q}^1(\beta)$ such that equality holds in all cases.

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