A first-order differential double subordination with applications

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Abstract

Let \(q_1\) and \(q_2\) belong to a certain class of normalized analytic univalent functions in the open unit disk of the complex plane. Sufficient conditions are obtained for normalized analytic functions \(p\) to satisfy the double subordination chain \(q_1(z) \prec p(z) \prec q_2(z)\). The differential sandwich-type result obtained is applied to normalized univalent functions and to \(\Phi\)-like functions.

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1. Introduction

Let \(\mathcal{H}\) be the class consisting of analytic functions in the open unit disk \(D := \{z \in \mathbb{C} : |z| < 1\}\) of the complex plane \(\mathbb{C}\). For \(a \in \mathbb{C}\), let \(\mathcal{H}(a,n) := \{f \in \mathcal{H} : f(z) = a + a_nz^n + a_{n+1}z^{n+1} + \cdots\}\), and \(\mathcal{A} := \{f \in \mathcal{H} : f(0) = 0, f'(0) = 1\}\). A function \(f \in \mathcal{H}\) is said to be subordinate to an analytic function \(g \in \mathcal{H}\), or \(g\) superordinates \(f\), written \(f(z) \prec g(z)\) \((z \in D)\), if there exists a Schwarz function \(w\), analytic in \(D\) with \(w(0) = 0\) and \(|w(z)| < 1\), satisfying \(f(z) = g(w(z))\). If the function \(g\) is univalent in \(D\), then \(f(z) \prec g(z)\) is equivalent to \(f(0) = g(0)\) and \(f(D) \subseteq g(D)\). An exposition on the widely used theory of differential subordination, developed in the main by Miller and Mocanu, with numerous applications to univalent functions can be found in their monograph \([14]\). Miller and Mocanu \([15]\) also introduced the dual concept of differential superordination. Let \(p,h \in \mathcal{H}\) and \(\phi(r,s,t;z) : \mathbb{C}^3 \times D \to \mathbb{C}\). If \(p\) and \(\phi(p(z),zp'(z),z^2p''(z);z)\) are univalent and \(p\) satisfies the second-order superordination

\[
h(z) \prec \phi(p(z),zp'(z),z^2p''(z);z),
\]

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then \( p \) is a solution of the differential superordination (1). An analytic function \( q \) is called a subordinant if \( q \prec p \) for all \( p \) satisfying (1). A univalent subordinant \( \tilde{q} \) satisfying \( q \prec \tilde{q} \) for all subordinants \( q \) of (1) is said to be the best subordinant. Miller and Mocanu [15] obtained conditions on \( h, q \) and \( \phi \) for which the following differential implication holds:

\[
\begin{align*}
    h(z) \prec \phi(p(z), zp'(z), z^2p''(z); z) & \Rightarrow q(z) \prec p(z).
\end{align*}
\]

Using these results, Bulboacă gave a treatment on certain classes of first-order differential superordinations [6, 8], as well as superordination-preserving integral operators [7]. Ali et al. [2] gave several applications of first-order differential subordination and superordination to obtain sufficient conditions for normalized analytic functions \( f \) to satisfy

\[
\begin{align*}
    q_1(z) & \prec \frac{zf''(z)}{f(z)} \prec q_2(z),
\end{align*}
\]

where \( q_1 \) and \( q_2 \) are given univalent analytic functions in \( D \). In [3] they have also applied differential superordination to functions defined by means of linear operators. Recently Ali and Ravichandran [1] investigated first-order superordination to a class of meromorphic \( \alpha \)-convex functions. Several differential subordination and superordination associated with various linear operators were also investigated in [4].

Generalizing the familiar starlike and convex functions, Lewandowski et al. [12] introduced \( \gamma \)-starlike functions consisting of \( f \in A \) satisfying the inequality

\[
\begin{align*}
    \text{Re} \left( \left( \frac{zf'(z)}{f(z)} \right)^{1-\gamma} \left( 1 + \frac{zf''(z)}{f(z)} \right)^\gamma \right) > 0.
\end{align*}
\]

These functions are starlike. With \( p(z) := \frac{zf'(z)}{f(z)} \), to show that \( \gamma \)-starlike functions are indeed starlike is to analytically make the implication

\[
\begin{align*}
    \text{Re} \left( p(z) \left( 1 + \frac{zp'(z)}{p(z)} \right)^\gamma \right) > 0 \Rightarrow \text{Re} p(z) > 0.
\end{align*}
\]

Following the work of Lewandowski et al. [12, 13], Kanas et al. [10] determined conditions on \( p \) and \( h \) satisfying

\[
\begin{align*}
    p(z) \left( 1 + \frac{zp'(z)}{p(z)} \right)^\alpha \prec h(z) \Rightarrow p(z) \prec h(z)
\end{align*}
\]

for a fixed \( \alpha \in [0, 1] \). Lecko [11] (see Kanas et al. [10] for a symmetric version) investigated the more general subordination

\[
\begin{align*}
    p(z) \left( 1 + \frac{zp'(z)}{p(z)} \phi(p(z)) \right)^\alpha \prec h(z) \Rightarrow p(z) \prec h(z).
\end{align*}
\]

Singh and Gupta [17] subsequently investigated the following first-order differential subordination that included the important Briot-Bouquet differential subordination:

\[
\begin{align*}
    (p(z)^\alpha \left( p(z) + \frac{zp'(z)}{\beta p(z) + \gamma} \right)^\mu \prec (q(z)^\alpha \left( q(z) + \frac{zq'(z)}{\beta q(z) + \gamma} \right)^\mu \Rightarrow p(z) \prec q(z).
\end{align*}
\]

For a closely related class, see S. Kanas and J. Kowalczyk [9].
The present paper investigates differential subordination and superordination implications of expressions similar to the form considered above by Singh and Gupta [17]. Special cases of the results obtained include one involving the expression \( ap^2(z) + (1 - \alpha)p(z) + \alpha zp'(z) \), a result which cannot be deduced from the work of Singh and Gupta [17]. The sandwich-type results obtained in our present investigation are then applied to normalized analytic univalent functions and to \( \Phi \)-like functions.

The following definition and results will be required:

**Lemma 1.1** (cf. Miller and Mocanu [14, Theorem 3.4h, p.132]). Let \( q \) be univalent in the unit disk \( \mathbb{D} \), and let \( \psi \) and \( \phi \) be analytic in a domain \( D \supset q(\mathbb{D}) \) with \( \phi(w) \neq 0, w \in q(\mathbb{D}) \). With \( Q(z) := zq'(z)\phi(q(z)) \), let \( h(z) := \psi(q(z)) + Q(z) \). Suppose that \( Q \) is starlike univalent in \( \mathbb{D} \) and

\[
\text{Re} \left( \frac{zh'(z)}{Q(z)} \right) > 0 \quad (z \in \mathbb{D}).
\]

If \( p \) is analytic in \( \mathbb{D} \) with \( p(0) = q(0) \), \( p(\mathbb{D}) \subseteq D \) and

\[
\psi(p(z)) + zp'(z)\phi(p(z)) \prec \psi(q(z)) + zq'(z)\phi(q(z)),
\]

then \( p(z) \prec q(z) \), and \( q \) is the best dominant.

**Definition 1.2** ([15, Definition 2, p. 817]). Denote by \( \mathcal{Q} \) the set of all functions \( f \) that are analytic and injective on \( \partial \mathbb{D} - E(f) \), where

\[
E(f) = \{ \zeta \in \partial \mathbb{D} : \lim_{z \to \zeta} f(z) = \infty \},
\]

and are such that \( f'(\zeta) \neq 0 \) for \( \zeta \in \partial \mathbb{D} - E(f) \).

**Lemma 1.3** ([18]). Let \( q \) be univalent in the unit disk \( \mathbb{D} \), \( \psi \) and \( \phi \) be analytic in a domain \( D \) containing \( q(\mathbb{D}) \). Suppose that \( \text{Re} \left[ \frac{\psi'(q(z))}{\phi(q(z))} \right] > 0 \) for \( z \in \mathbb{D} \) and \( zq'(z)\phi(q(z)) \) is starlike univalent in \( \mathbb{D} \). If \( p \in \mathcal{H}(q(0), 1] \cap \mathcal{Q} \) with \( p(\mathbb{D}) \subseteq D \), and \( \psi(p(z)) + zp'(z)\phi(p(z)) \) is univalent in \( \mathbb{D} \), then

\[
\psi(q(z)) + zq'(z)\phi(q(z)) \prec \psi(p(z)) + zp'(z)\phi(p(z))
\]

implies \( q(z) \prec p(z) \), and \( q \) is the best subordinant.

2. A Sandwich Theorem

Our main result involves the following class of functions:

**Definition 2.1.** Let \( \alpha \) and \( \mu \) be fixed numbers with \( 0 < \mu \leq 1 \), \( \alpha + \mu \geq 0 \). Also let \( \beta, \gamma \) and \( \delta \) be complex numbers with \( \beta \neq 0 \). The class \( \mathcal{M}(\alpha, \beta, \gamma, \delta, \mu) \) consists of analytic functions \( p \) with \( p(0) = 1, p(z) \neq 0 \) in \( \mathbb{D} \), and are such that the functions

\[
P(z) := (p(z))^\alpha \left( p(z) + \delta + \frac{zp'(z)}{\beta p(z) + \gamma} \right)^\mu \quad (z \in \mathbb{D})
\]

are well-defined in \( \mathbb{D} \). (Here the powers are principal values.)
By making use of Lemma [1.1] the following result is derived:

**Theorem 2.2.** Let $q \in S(\alpha, \beta, \gamma, \delta, \mu)$ be analytic and univalent in $\mathbb{D}$. Set

\[ R(z) := \frac{zq'(z)}{\beta q(z) + \gamma} \quad (z \in \mathbb{D}). \]  

Assume that

\[ \text{Re} \left( \left( \beta q(z) + \gamma \right) \left( 1 + \frac{\alpha}{\mu} + \frac{\alpha \delta}{\mu q(z)} \right) \right) > 0 \quad (z \in \mathbb{D}), \]  

and

\[ \text{Re} \left( \frac{\alpha zq'(z)}{\mu q(z)} + \frac{zR'(z)}{R(z)} \right) > 0 \quad (z \in \mathbb{D}). \]  

If $p \in S(\alpha, \beta, \gamma, \delta, \mu)$ satisfies

\[ (p(z))^\alpha \left( p(z) + \delta + \frac{zp'(z)}{\beta p(z) + \gamma} \right)^\mu < (q(z))^\alpha \left( q(z) + \delta + \frac{zq'(z)}{\beta q(z) + \gamma} \right)^\mu, \]  

then $p(z) \prec q(z)$, and $q$ is the best dominant.

**Proof.** We first write the differential subordination (5) as

\[ (p(z))^\frac{\mu}{\alpha} + \delta (p(z))^\frac{\mu}{\alpha} + (p(z))^\frac{\mu}{\alpha} \frac{zp'(z)}{\beta p(z) + \gamma} < (q(z))^\frac{\mu}{\alpha} + \delta (q(z))^\frac{\mu}{\alpha} + (q(z))^\frac{\mu}{\alpha} \frac{zq'(z)}{\beta q(z) + \gamma}. \]

Define the functions $\vartheta$ and $\varphi$ by

\[ \vartheta(w) := w^{\frac{\mu}{\alpha} + 1} + \delta w^{\frac{\mu}{\alpha}} \quad \text{and} \quad \varphi(w) := \frac{w^{\frac{\mu}{\alpha}}}{\beta w + \gamma}. \]

Since $q \in S(\alpha, \beta, \gamma, \delta, \mu)$, then $q(z) \neq 0$ and therefore $\varphi(w) \neq 0$ when $w \in q(\mathbb{D})$. Also $\varphi$ and $\vartheta$ are analytic in a domain containing $q(\mathbb{D})$. Define the function

\[ Q(z) := zq'(z)\varphi(q(z)) = (q(z))^{\frac{\mu}{\alpha}} \frac{zq'(z)}{\beta q(z) + \gamma} = (q(z))^{\frac{\mu}{\alpha}} R(z), \]

where $R$ is given by (2). It follows from (4) that

\[ \text{Re} \frac{zQ'(z)}{Q(z)} = \text{Re} \left( \frac{\alpha zq'(z)}{\mu q(z)} + \frac{zR'(z)}{R(z)} \right) > 0, \]

and so $Q$ is a starlike function. Now define $h$ by

\[ h(z) := \vartheta(q(z)) + Q(z) = (q(z))^{\frac{\mu}{\alpha} + 1} + \delta (q(z))^{\frac{\mu}{\alpha}} + Q(z). \]

In view of the assumptions (3) and (4), it follows that

\[ \text{Re} \frac{zh'(z)}{Q(z)} = \text{Re} \left\{ (\beta q(z) + \gamma) \left( 1 + \frac{\alpha}{\mu} + \frac{\alpha \delta}{\mu q(z)} \right) + \frac{\alpha zq'(z)}{\mu q(z)} + \frac{zR'(z)}{R(z)} \right\} > 0 \quad (z \in \mathbb{D}). \]

The result is now deduced from Lemma [1.1].
Example 2.3. Let \( q : \mathbb{D} \to \mathbb{C} \) be defined by \( q(z) = (1 + Az)/(1 + Bz) \) with \(-1 < B < A \leq 1\). It is evident that \( q \in \mathcal{R}(\alpha, \beta, \gamma, \delta, \mu) \) whenever

\[
\delta + \frac{1 - A}{1 - B} > \frac{A - B}{(1 - B)|\beta + \gamma| - |\beta A + \gamma B|}.
\]

With additional constraints on the parameters, there exists functions \( q \) satisfying the hypothesis of Theorem 2.2. For instance, in addition to the above condition, assuming all the parameters \( \alpha, \beta, \gamma, \delta, \) and \( \mu \) are positive with

\[
\frac{1 - 2A}{1 - A} > \frac{|\beta A + \gamma B|}{|\beta + \gamma - |\beta A + \gamma B||},
\]

then \( q \) satisfies the conditions of Theorem 2.2.

By a similar application of Lemma 1.3, the following result can be established, which we state without proof.

**Theorem 2.4.** Let \( q \in \mathcal{R}(\alpha, \beta, \gamma, \delta, \mu) \) be as in Theorem 2.2. Let \( p \in \mathcal{R}(\alpha, \beta, \gamma, \delta, \mu) \) satisfies \( p \in \mathcal{H} \cap \mathcal{Q} \) and \( (p(z))^{\frac{\mu}{\beta}} + \delta(p(z))^{\frac{\alpha}{\beta}} + (p(z))^{\frac{\mu}{\beta}} z p'(z)_{\beta p(z) + \gamma} \) be univalent. If \( p \) satisfies

\[
(q(z))^\alpha \left( q(z) + \delta + \frac{z q'(z)}{\beta q(z) + \gamma} \right) + (p(z))^\alpha \left( p(z) + \delta + \frac{z p'(z)}{\beta p(z) + \gamma} \right) < 0,
\]

then \( q(z) \prec p(z) \), and \( q \) is the best subordinant.

Combining Theorems 2.2 and 2.4 the following "sandwich theorem" is obtained:

**Theorem 2.5.** Let \( q_i \in \mathcal{R}(\alpha, \beta, \gamma, \delta, \mu) \) \( (i = 1, 2) \) be analytic and univalent in \( \mathbb{D} \). Set

\[
R_i(z) := \frac{z q'_i(z)}{\beta q_i(z) + \gamma} \quad (i = 1, 2; z \in \mathbb{D}),
\]

\[
h_i(z) := (q_i(z))^\alpha \left( q_i(z) + \delta + \frac{z q'_i(z)}{\beta q_i(z) + \gamma} \right) \quad (i = 1, 2).
\]

Assume that

\[
\text{Re} \left( (\beta q_i(z) + \gamma) \left( 1 + \frac{\alpha}{\mu} + \frac{\alpha \delta}{\mu q_i(z)} \right) \right) > 0 \quad (z \in \mathbb{D})
\]

and

\[
\text{Re} \left( \frac{\alpha}{\mu} \frac{z q'_i(z)}{R_i(z)} + \frac{z R'_i(z)}{R_i(z)} \right) > 0 \quad (i = 1, 2; z \in \mathbb{D}).
\]

If \( p \in \mathcal{R}(\alpha, \beta, \gamma, \delta, \mu) \) satisfies \( p \in \mathcal{H} \cap \mathcal{Q} \) and \( (p(z))^{\frac{\mu}{\beta}} + \delta(p(z))^{\frac{\alpha}{\beta}} + (p(z))^{\frac{\mu}{\beta}} z p'(z)_{\beta p(z) + \gamma} \) is univalent, then

\[
h_1(z) \prec (p(z))^\alpha \left( p(z) + \delta + \frac{z p'(z)}{\beta p(z) + \gamma} \right) \prec h_2(z)
\]

implies \( q_1(z) \prec p(z) \prec q_2(z) \). Further \( q_1 \) and \( q_2 \) are respectively the best subordinant and the best dominant.

5
3. Applications to Univalent Functions

By use of Theorem 2.5, the following result is obtained:

**Theorem 3.1.** Let \( \alpha, \mu \) be fixed numbers with \( 0 < \mu \leq 1, \alpha + \mu > 0, \) and \( \lambda \in \mathbb{C}. \) Let \( f, g \in \mathcal{A}, \) and \( q_i(z) = zg'_i(z)/g_i(z) \) \((i = 1, 2)\) be univalent in \( \mathbb{D} \) satisfying

\[
\Re \left( \frac{1}{\lambda} q_i(z) \right) > 0
\]

and

\[
\Re \left( \left( \frac{\alpha}{\mu} - 1 \right) \frac{zg'_i(z)}{g_i(z)} + 1 + \frac{zg''_i(z)}{q'_i(z)} \right) > 0.
\]

Let

\[
h_i(z) := \left( \frac{zg'_i(z)}{g_i(z)} \right)^\alpha \left( 1 - \lambda \right) \frac{zg'_i(z)}{g_i(z)} + \lambda \left( 1 + \frac{zg''_i(z)}{g_i(z)} \right)^\mu \quad (i = 1, 2).
\]

If \( f \in \mathcal{A} \) satisfies \( 0 \neq zf'(z)/f(z) \in \mathcal{H}[1, 1] \cap \mathcal{D} \) and \( \left( \frac{zf'(z)}{f(z)} \right)^\alpha \left( 1 - \lambda \right) \frac{zf'(z)}{f(z)} + \lambda \left( 1 + \frac{zf''(z)}{f'(z)} \right)^\mu \) is univalent in \( \mathbb{D}, \) then

\[
h_1(z) \prec \left( \frac{zf'(z)}{f(z)} \right)^\alpha \left( 1 - \lambda \right) \frac{zf'(z)}{f(z)} + \lambda \left( 1 + \frac{zf''(z)}{f'(z)} \right)^\mu \prec h_2(z)
\]

implies

\[
\frac{zg'_i(z)}{g_i(z)} \prec \frac{zf'(z)}{f(z)} \prec \frac{zg''_i(z)}{g_i(z)}.
\]

**Proof.** The result follows from Theorem 2.5 by taking \( \gamma = \delta = 0, \beta = 1/\lambda, \) and

\[
p(z) := \frac{zf'(z)}{f(z)} \quad \text{and} \quad q_i(z) := \frac{zg'_i(z)}{g_i(z)} \quad (i = 1, 2).
\]

The following two corollaries are immediate consequences of Theorem 2.5 (or Theorem 3.1):

**Corollary 3.2.** Let \( \alpha \in \mathbb{C}, \) and \( q_i(z) \neq 0 \) \((i = 1, 2)\) be univalent in \( \mathbb{D}. \) Assume that \( \Re [\alpha q_i(z)] > 0 \) for \( i = 1, 2 \) and \( zq'_i(z)/q_i(z) \) \((i = 1, 2)\) is starlike univalent in \( \mathbb{D}. \) If \( f \in \mathcal{A}, \) \( 0 \neq zf'(z)/f(z) \in \mathcal{H}[1, 1] \cap \mathcal{D}, \) \((1 - \alpha)z^2(z) + \alpha \left( 1 + \frac{zf''(z)}{f'(z)} \right) \) is univalent in \( \mathbb{D}, \) then

\[
q_1(z) + \alpha \frac{zg'_i(z)}{q_1(z)} \prec \left( 1 - \alpha \right) \frac{zf'(z)}{f(z)} + \alpha \left( 1 + \frac{zf''(z)}{f'(z)} \right) \prec q_2(z) + \alpha \frac{zg''_i(z)}{q_2(z)}
\]

implies

\[
q_1(z) \prec \frac{zf'(z)}{f(z)} \prec q_2(z).
\]

Further \( q_1 \) and \( q_2 \) are respectively the best subordinant and best dominant.
**Corollary 3.3.** Let $q_i(z) \neq 0$ be univalent in $\mathbb{D}$ with $\text{Re} q_i(z) > 0$. Let $z q_i'(z)/q_i^2(z)$ be starlike univalent in $\mathbb{D}$ for $i = 1, 2$. If $f \in \mathcal{A}$, $0 \neq z f'(z)/f(z) \in \mathcal{H} \cap Q$, $\frac{1 + z f'''(z)/f'(z)}{z f'(z)/f(z)}$ is univalent in $\mathbb{D}$, then

$$1 + \frac{z q_1'(z)}{q_1(z)} < \frac{1 + z f''(z)/f'(z)}{z f'(z)/f(z)} < 1 + \frac{z q_2'(z)}{q_2(z)}$$

implies $q_1(z) < z f'(z)/f(z) < q_2(z)$. Further $q_1$ and $q_2$ are respectively the best subordinant and best dominant.

Another application of Theorem 2.5 yields the following result:

**Corollary 3.4.** Let $q_1$ and $q_2$ be convex univalent in $\mathbb{D}$. Let $0 \neq \alpha \in \mathbb{C}$, and assume that $\text{Re} q_i(z) > \text{Re} \frac{q_i(z)}{2\alpha}$ for $i = 1, 2$. If $f \in \mathcal{A}$, $z f'(z)/f(z) \in \mathcal{H} \cap \mathcal{D}$, $\frac{z f'(z)}{f(z)} + \alpha \frac{z^2 f''(z)}{f'(z)}$ is univalent in $\mathbb{D}$, then

$$(1 - \alpha)q_1(z) + \alpha q_1^2(z) + \alpha z q_1'(z) < \frac{z f'(z)}{f(z)} \left(1 + \alpha \frac{z f''(z)}{f'(z)}\right) < (1 - \alpha)q_2(z) + \alpha q_2^2(z) + \alpha z q_2'(z)$$

implies

$$q_1(z) < \frac{z f'(z)}{f(z)} < q_2(z).$$

Further $q_1$ and $q_2$ are respectively the best subordinant and best dominant.

4. Application to $\Phi$-like Functions

Let $\Phi$ be an analytic function in a domain containing $f(\mathbb{D})$, $\Phi(0) = 0$ and $\Phi'(0) > 0$. A function $f \in \mathcal{A}$ is called $\Phi$-like if

$$\text{Re} \frac{z f'(z)}{\Phi(f(z))} > 0 \quad (z \in \mathbb{D}).$$

This concept was introduced by Brickman [5] and it was shown that an analytic function $f \in \mathcal{A}$ is univalent if and only if $f$ is $\Phi$-like for some $\Phi$. When $\Phi(w) = w$ and $\Phi'(w) = \lambda w$, the $\Phi$-like function $f$ is respectively starlike and spirallike of type arg $\lambda$. Ruscheweyh [16] introduced and studied the following general class of $\Phi$-like functions:

**Definition 4.1.** Let $\Phi$ be analytic in a domain containing $f(\mathbb{D})$, $\Phi(0) = 0$, $\Phi'(0) = 1$ and $\Phi(\omega) \neq 0$ for $\omega \in f(\mathbb{D}) - \{0\}$. Let $q$ be a fixed analytic function in $\mathbb{D}$, with $q(0) = 1$. A function $f \in \mathcal{A}$ is called $\Phi$-like with respect to $q$ if

$$\frac{z f'(z)}{\Phi(f(z))} < q(z) \quad (z \in \mathbb{D}).$$
Theorem 4.2. Let $\alpha \neq 0$ be a complex number and $q_i\ (i = 1, 2)$ be convex univalent in $\mathbb{D}$. Define $h_i$ by

$$h_i(z) := \alpha q_i^2(z) + (1 - \alpha)q_i(z) + \alpha z q_i'(z) \quad (i = 1, 2),$$

and suppose that

$$\text{Re} \left( \frac{1 - \alpha}{\alpha} + 2q_i(z) \right) > 0 \quad (i = 1, 2; z \in \mathbb{D}).$$

If $f \in \mathcal{A}$ satisfies $f \in \mathcal{H}[1, 1] \cap \mathcal{Q}$ and

$$zf'(z) \left( 1 + \frac{\alpha zf''(z)}{f'(z)} + \frac{\alpha (f'(z) - (\Phi(f(z)))')}{\Phi(f(z))} \right)$$

is univalent in $\mathbb{D}$, then

$$h_1(z) \prec \alpha p^2(z) + (1 - \alpha)p(z) + \alpha z p'(z) \prec \alpha p^2(z) + (1 - \alpha)p(z) + \alpha z p'(z) \prec h_2(z)$$

implies

$$q_1(z) \prec \frac{zf'(z)}{\Phi(f(z))} \prec q_2(z).$$

Further $q_1$ and $q_2$ are respectively the best subordinant and the best dominant.

Proof. Define the function $p$ by

$$p(z) := \frac{zf'(z)}{\Phi(f(z))} \quad (z \in \mathbb{D}). \quad (8)$$

Then the function $p$ is analytic in $\mathbb{D}$ with $p(0) = 1$. From (8), it follows that

$$zf'(z) \left( 1 + \frac{\alpha zf''(z)}{f'(z)} + \frac{\alpha (f'(z) - (\Phi(f(z)))')}{\Phi(f(z))} \right)$$

$$= p(z) \left( 1 + \alpha \left( \frac{zp'(z)}{p(z)} - 1 \right) + \alpha p(z) \right)$$

$$= \alpha p^2(z) + (1 - \alpha)p(z) + \alpha z p'(z). \quad (9)$$

Putting (9) in the subordination (7) yields

$$h_1(z) \prec \alpha p^2(z) + (1 - \alpha)p(z) + \alpha z p'(z) \prec h_2(z).$$

The result now follows from Theorem 2.5. \qed

Remark 1. When $\Phi(w) = w$, Theorem 4.2 reduces to Corollary 3.4.
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