Distortion Theorem for Fractional Integral Operator

Tadayuki SEKINE * [関根忠行]（日大薬学部）

Abstract
We define the generalized subclasses of the class consisting of analytic functions with negative coefficients. We obtain the distortion theorem on functions in the generalized subclasses for fractional integral operator involving the generalized hypergeometric function.

1 Introduction and Definitions

Let $A(n, p)$ denote the class of functions of the form

$$f(z) = z - \sum_{k=n+p}^{\infty} a_k z^k \quad (a_k \geq 0; \ n, p \in N) \quad (1)$$

that are analytic in the unit disk $U = \{z : |z| < 1\}$. Let $A(n, p; \{B_k\})$ denote the subclass of $A(n, p)$ consisting of functions which satisfy the following inequality:

$$\sum_{k=n+p}^{\infty} B_k a_n \leq 1 \quad (B_k > 0; \ n, p \in N). \quad (2)$$

The subclasses $A(n, p; \{B_k\})$ is called the generalized subclasses of the class consisting of analytic functions with negative coefficients. The case of $p=1$ and the case of arbitrarily positive integer $p$ were considered by Sekine [4], and Owa and Obradvic[3], respectively.

In [4], we expressed various known subclasses of the class consisting of the functions with negative coefficients in terms of the generalized subclasses and obtained inclusion relation of these classes. We gave distortion theorems on the derivatives of integer order of functions belonging to the generalized classes. Further using the fractional integral,

*Department of Mathematics, College of Pharmacy, Nihon University, 7-7-1, Narashinodai, Funabashi-shi, Chiba 274 Japan
fractional derivative by Owa[2] and the fractional integral operator by Srivastava, Saigo and Owa[6], we extend the distortion theorems on the derivative of arbitrary order of functions in the generalized subclasses.

Let $\alpha_j (j = 1, \cdots, p)$ and $\beta_j (j = 1, \cdots, q)$ be complex numbers with

$$\beta_j \neq 0, -1, -2, \cdots \quad (j = 1, \cdots, q).$$

Then the generalized hypergeometric function $p F_q(z)$ is defined by

$$p F_q \equiv p F_q(\alpha_1, \cdots, \alpha_p; \beta_1, \cdots, \beta_q; z)$$

$$= \frac{\Gamma(\lambda + n)}{\Gamma(\lambda)} \frac{(\alpha_1)_n \cdots (\alpha_p)_n (\beta_1)_n \cdots (\beta_q)_n}{n!} z^n \quad (p \leq q + 1),$$

where $(\lambda)_n$ is the pochhammer symbol defined by

$$(\lambda)_n \equiv \frac{\Gamma(\lambda + n)}{\Gamma(\lambda)} = \begin{cases} \lambda(\lambda + 1) \cdots (\lambda + n - 1), & n \in N = \{1, 2, 3, \cdots\}, \\ 1, & n = 0. \end{cases}$$

Many essentially equivalent definitions of fractional calculus have been given. We state the following definitions due to Owa[2] which have been used rather frequently in the theory of analytic function:

**Definition 1.1 (Owa[2])** The fractional integral of order $\lambda$ is defined by

$$D_z^\lambda f(z) = \frac{1}{\Gamma(\lambda)} \int_0^z \frac{f(\xi)}{(z-\xi)^{1-\lambda}} d\xi$$

where $\lambda > 0$, $f(z)$ is an analytic function in a simply connected region of the $z$-plane containing the origin and the many-valuedness of $(z-\xi)^{\lambda-1}$ is removed by requiring $\log(z-\xi)$ to be real when $(z-\xi) > 0$.

**Definition 1.2 (Owa[2])** The fractional derivative of order $\lambda$ is defined by

$$D_z^\lambda f(z) = \frac{1}{\Gamma(1-\lambda)} \frac{d}{dz} \int_0^z \frac{f(\xi)}{(z-\xi)^{1-\lambda}} d\xi$$

where $0 \leq \lambda < 1$, $f(z)$ is an analytic function in a simply connected region of the $z$-plane containing the origin and the many-valuedness of $(z-\xi)^{-\lambda}$ is removed by requiring $\log(z-\xi)$ to be real when $(z-\xi) > 0$. 
Definition 1.3 (Owa[2]) Under the hypotheses of Definition 1.2, the fractional derivative of order \((n + \lambda)\) is defined by

\[
D_z^{n+\lambda}f(z) = \frac{d^n}{dz^n}D_z^\lambda f(z)
\]  
(7)

where \(0 \leq \lambda < 1\) and \(n \in \mathbb{N}_0 = \{0, 1, 2, \cdots\}\).

Srivastava, Saigo and Owa defined the following fractional integral operator involving Gauss's hypergeometric function:

Definition 1.4 (Srivastava, Saigo and Owa[6]) For real number \(\alpha > 0\), \(\beta\) and \(\eta\), the fractional integral operator \(I_{0,z}^{\alpha,\beta,\eta}\) is defined by

\[
I_{0,z}^{\alpha,\beta,\eta}f(z) = \frac{z^{-\alpha-\beta}}{\Gamma(\alpha)}\int_0^z (z-\zeta)^{\alpha-1}F\left(\alpha + \beta, -\eta; \alpha; 1 - \frac{\zeta}{z}\right)f(\zeta)d\zeta
\]  
(8)

where \(f(z)\) is an analytic function in a simply-connected region of the \(z\)-plane containing the origin with the order

\[
f(z) = O(|z|^\epsilon), \quad \text{as } z \to 0,
\]

where \(\epsilon > \max\{0, \beta-\eta\}-1\) and the many-valuedness of \((z-\xi)^{\alpha-1}\) is removed by requiring \(\log(z-\xi)\) to be real when \((z-\xi) > 0\).

From Definition 1.1 and Definition 1.4, it is easy to see that

\[
D_z^{-\alpha}f(z) = I_{0,z}^{\alpha,-\alpha,\eta}f(z).
\]

Lemma 1.1 (Srivastava, Saigo and Owa[6]) If \(\alpha > 0\) and \(k > \beta - \eta - 1\), then

\[
I_{0,z}^{\alpha,\beta,\eta}z^k = \frac{\Gamma(k+1)\Gamma(k-\beta+\eta+1)}{\Gamma(k-\beta+1)\Gamma(k+\alpha+\eta+1)}z^{k-\beta}.
\]

Using Definition 1.4 and Lemma 1.1 above, we showed the following result:

Theorem 1.1 ([5]) Let \(\alpha, \beta\) and \(\eta\) satisfy the inequalities, \(\alpha > 0\), \(\beta < p + 1\), \(\alpha + \eta > -(p + 1)\), \(\beta - \eta < p + 1\). Choose a positive integer \(n\) such that

\[
n \geq \frac{\beta(\alpha + \eta)}{\alpha} - p - 1.
\]
If \( f(z) \in A(n,p, \{ B_k \} \) and \( B_k \geq B_{k+1} \), then
\[
|I_{0,z}^{\alpha,\beta,\eta} f(z)| \leq \max \left[ 0, \frac{\Gamma(p+1)\Gamma(p+\alpha+\eta+1)}{\Gamma(p+1-\beta+1)\Gamma(p+\alpha+\eta+1)} |z|^{p-\beta} \right.
\times \left. \left\{ 1 - \frac{(p+1-\beta+\eta)_{n}(p+1)_{n}}{(p+1-\beta)n(p+1+\alpha+\eta)_{n}B_{n+p}} |z|^{n} \right\} \right]
\] (9)
and
\[
|I_{0,z}^{\alpha,\beta,\eta} f(z)| \leq \frac{\Gamma(p+1)\Gamma(p+1-\beta+1)\Gamma(p+\alpha+\eta+1)}{\Gamma(p+1-\beta+1)\Gamma(p+\alpha+\eta+1)} |z|^{p-\beta} \times \left\{ 1 + \frac{(p+1-\beta+\eta)_{n}(p+1)_{n}}{(p+1-\beta)n(p+1+\alpha+\eta)_{n}B_{n+p}} |z|^{n} \right\}
\] (10)
for \( z \in U_0 \), where
\[
U_0 = \begin{cases} U, & \beta \leq p, \\ U - \{0\}, & \beta > p \end{cases}
\]
and \((\lambda)_n\) is the pochhammer symbol defined by (4).

Equalities fold for the function defined by
\[
f(z) = z^p - \frac{1}{B_{n+p}}z^{n+p}.
\]

Recently, Choi, Kim, and Srivastava defined the following generalized operator of fractional calculus:

**Definition 1.5 (Choi, Kim and Srivastava[1])** Let \( \alpha, m \in R^+ \), and \( \beta, \eta \in R \). Then the fractional integral operator \( I_{0,z}^{\alpha,\beta,\eta} \) is defined by
\[
I_{0,z}^{\alpha,\beta,\eta} f(z) = \frac{z^{-m(\alpha+\beta)}}{\Gamma(\alpha)} \int_{0}^{z} (z^m - \xi^m)^{\alpha-1} \frac{\xi^m}{z^m} 2F_1 \left[ \alpha + \beta, -\eta; \alpha; 1 - \frac{\xi^m}{z^m} \right] f(\xi) d(\xi^m)
\] (11)
where the function \( 2F_1 \) is Gauss's hypergeometric function defined by (3) with \( p-1 = q = 1 \).

and \( f(z) \) is an analytic function in a simply-connected region of the \( z \)-plane containing the origin with the order
\[
f(z) = O(|z|^r), \quad z \to 0
\]
where \( r > \max\{0, m(\beta - \eta)\} - m \), and the multiplicity of \( (z^m - \zeta^m)^{\alpha-1} \) is removed by requiring \( \log(z^m - \zeta^m) \) to be real when \( (z^m - \zeta^m) > 0 \).
It is easy to observe that
\[ I_{0,z;1}^{\alpha,-\alpha,n} f(z) = I_{0,z}^{\alpha,-\alpha,n} f(z). \]

We need the following Lemma:

**Lemma 1.2** If \( \alpha > 0 \) and \( \frac{k}{m} > \beta - \eta - 1 \), then

\[ I_{0,z}^{\alpha,\beta,\eta} = \frac{\Gamma \left( \frac{k}{m} + 1 \right) \Gamma \left( \frac{k}{m} + 1 - \beta + \eta \right)}{\Gamma \left( \frac{k}{m} + 1 - \beta \right) \Gamma \left( \frac{k}{m} + 1 + \alpha + \eta \right)} z^{k-m}. \]

**Proof.** We shall prove Lemma 1.2 in a similar fashion to the proof of Lemma 1.1 by Srivastava, Saigo and Owa\[6\].

\[
I_{0,z;1}^{\alpha,\beta,\eta} = \frac{z}{\Gamma(\alpha)} \int_0^z (z^m - \xi)^{a-1} F_1 \left( \alpha + \beta, -\eta; \alpha; 1 - \frac{\xi}{z} \right) \xi^k d(\xi^m) 
\]

\[
= \frac{z}{\Gamma(\alpha)} \int_0^z (z^m - h)^{a-1} F_1 \left( \alpha + \beta, -\eta; \alpha; 1 - \frac{h}{z} \right) h^k dh \tag{13}
\]

\[
= \frac{z}{\Gamma(\alpha)} \int_0^1 e^{-t} (1 - t)^{\frac{k}{m}} \left( \frac{k}{m} \right) F \left( \alpha + \beta, -\eta; \frac{k}{m} \alpha + 1; 1 \right) \right)
\]

\[
= \frac{\Gamma \left( \frac{k}{m} + 1 \right) \Gamma \left( \frac{k}{m} + \alpha + 1 \right)}{\Gamma \left( \frac{k}{m} + 1 - \beta \right) \Gamma \left( \frac{k}{m} + 1 + \alpha + \eta \right)} z^{k-m}. \tag{14}
\]
2 Distortion theorem

Theorem 2.1 Let $m \in \mathbb{N}$ and $\alpha, \beta$ and $\eta$ satisfy the inequalities $\alpha > 0$, $\beta < \frac{p}{m} + 1$, $\alpha + \eta > -\left(\frac{p}{m} + 1\right)$ and $\beta - \eta < \frac{p}{m} + 1$. Choose a positive integer $n$ such that

$$n \geq \frac{m\beta(\alpha + \eta)}{\alpha} - m - p.$$

If $f(z) \in A(n, p; \{B_k\})$ and $B_k \leq B_{k+1}$, then

$$|I_{0, \cdot m}^{\alpha\beta, \eta}f(z)| \geq \max \left[0, \frac{\Gamma\left(\frac{p}{m} + 1\right) \Gamma\left(\frac{p}{m} + 1 - \beta + \eta\right)}{\Gamma\left(\frac{p}{m} + 1 - \beta\right) \Gamma\left(\frac{p}{m} + 1 + \alpha + \eta\right)} |z|^{p-m\beta} \right.$$

$$\times \left\{1 \left[1 - \frac{\Gamma\left(\frac{p}{m} + 1 - \beta\right) \Gamma\left(\frac{p}{m} + 1 + \alpha + \eta\right)}{\Gamma\left(\frac{p}{m} + 1\right) \Gamma\left(\frac{p}{m} + 1 - \beta + \eta\right)} \frac{\delta_m}{B_{n+p}} |z|^n \right\} \right] (15)$$

and

$$|I_{0, \cdot m}^{\alpha, \beta, \eta}f(z)| \leq \frac{\Gamma\left(\frac{p}{m} + 1\right) \Gamma\left(\frac{p}{m} + 1 - \beta + \eta\right)}{\Gamma\left(\frac{p}{m} + 1 - \beta\right) \Gamma\left(\frac{p}{m} + 1 + \alpha + \eta\right)} |z|^{p-m\beta}$$

$$\times \left\{1 + \frac{\Gamma\left(\frac{p}{m} + 1 - \beta\right) \Gamma\left(\frac{p}{m} + 1 + \alpha + \eta\right)}{\Gamma\left(\frac{p}{m} + 1\right) \Gamma\left(\frac{p}{m} + 1 - \beta + \eta\right)} \frac{\delta_m}{B_{n+p}} |z|^n \right\} (16)$$

for $z \in U_0$ where

$$U_0 = \left\{ U, \ m\beta \leq p, \ U - \{0\}, \ m\beta > p \right\}$$

and $\delta_m$ is given by

$$\delta_m = \max_{n+p \leq k \leq n+p+m-1} \{\psi(k)\},$$

where

$$\psi(k) = \frac{\Gamma\left(\frac{k}{m} + 1\right) \Gamma\left(\frac{k}{m} + 1 - \beta + \eta\right)}{\Gamma\left(\frac{k}{m} + 1 - \beta\right) \Gamma\left(\frac{k}{m} + 1 + \alpha + \eta\right)}.$$
Proof. Define a function $\Psi(z)$ by

$$\Psi(z) = \frac{\Gamma\left(\frac{p}{m} + 1 - \beta\right) \Gamma\left(\frac{p}{m} + 1 + \alpha + \eta\right)}{\Gamma\left(\frac{p}{m} + 1\right) \Gamma\left(\frac{p}{m} + 1 - \beta + \eta\right)} z^{m\beta} I_{0, z}^\alpha' ; \beta, \eta ; m(z).$$

(17)

Then, by virtue of Lemma 1.2, we have

$$\Psi(z) = z^p - \sum_{k=n+p}^{\infty} \frac{\Gamma\left(\frac{k}{m} + 1\right) \Gamma\left(\frac{k}{m} + 1 - \beta + \eta\right)}{\Gamma\left(\frac{k}{m} + 1 - \beta\right) \Gamma\left(\frac{k}{m} + 1 + \alpha + \eta\right)} a_k z^k$$

(18)

where

$$\Phi = \frac{\Gamma\left(\frac{p}{m} + 1 - \beta\right) \Gamma\left(\frac{p}{m} + 1 + \alpha + \eta\right)}{\Gamma\left(\frac{p}{m} + 1\right) \Gamma\left(\frac{p}{m} + 1 - \beta + \eta\right)}$$

$$\psi(k) = \frac{\Gamma\left(\frac{k}{m} + 1\right) \Gamma\left(\frac{k}{m} + 1 - \beta + \eta\right)}{\Gamma\left(\frac{k}{m} + 1 - \beta\right) \Gamma\left(\frac{k}{m} + 1 + \alpha + \eta\right)}.$$

For a positive integer $n$ such that

$$n \geq \frac{m\beta(\alpha + \eta)}{\alpha} - m - p,$$

we have

$$0 < \psi(k + m) \leq \psi(k) \quad (k \geq n + p).$$

Hence, defining $\delta_m$ by

$$\delta_m = \max\{\psi(n + p), \psi(n + p + 1), \psi(n + p + 2), \ldots, \psi(n + p + m - 1)\},$$
we have
\[ 0 < \psi(k) \leq \delta_m \quad (k \geq n + p). \]

Therefore, we have that
\[
|\Phi(z)| \leq |z|^p + \sum_{k=n+p}^{\infty} \phi \psi(k) a_k |z|^k
\]
\[
\leq |z|^p + \Phi \delta_m |z|^{n+p} \sum_{k=n+p}^{\infty} a_k
\]
\[
\leq |z|^p + \Phi \delta_m |z|^{n+p} \frac{1}{B_{n+p}}. \tag{19}
\]

We have the last inequality above, because
\[
\sum_{k=n+p}^{\infty} a_k \leq \frac{1}{B_{n+p}}
\]
by the assumption of the theorem such that \( f(z) \in A(n, p; \{B_k\}) \) and \( B_k \leq B_{k+1} \).

In the same manner, we have
\[
|\Phi(z)| \geq \max \left\{ 0, |z|^p - \Phi \delta_m |z|^{n+p} \frac{1}{B_{n+p}} \right\}. \tag{20}
\]

By virtue of (17), these estimates (19) and (20) lead to (15) and (16), respectively.

**Remark 2.1** If \( m = 1 \) in Theorem 2.1, then we have Theorem 1.1([5]).

**References**


