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INTEGRAL MEANS INEQUALITIES FOR FRACTIONAL DERIVATIVES OF SOME GENERAL SUBCLASSES OF ANALYTIC FUNCTIONS

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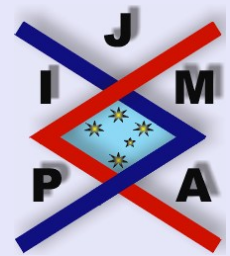
Abstract

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Abstract

Integral means inequalities are obtained for the fractional derivatives of order $p + \lambda \; (0 \leqq p \leqq n; \; 0 \leqq \lambda < 1)$ of functions belonging to certain general subclasses of analytic functions. Relevant connections with various known integral means inequalities are also pointed out.

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1. Introduction, Definitions, and Preliminaries

Let $\mathcal{A}$ denote the class of functions $f(z)$ *normalized* by

$$f(z) = z + \sum_{k=2}^{\infty} a_k z^k$$

that are *analytic* in the *open* unit disk

$$\mathbb{U} := \{z : z \in \mathbb{C} \quad \text{and} \quad |z| < 1\}.$$

Also let $\mathcal{A}(n)$ denote the subclass of $\mathcal{A}$ consisting of all functions $f(z)$ of the form:

$$f(z) = z - \sum_{k=n+1}^{\infty} a_k z^k \quad (a_k \geqq 0; \ n \in \mathbb{N} := \{1, 2, 3, \ldots\}).$$

We denote by $\mathcal{T}(n)$ the subclass of $\mathcal{A}(n)$ of functions which are *univalent* in $\mathbb{U}$, and by $\mathcal{T}_\alpha(n)$ and $\mathcal{C}_\alpha(n)$ the subclasses of $\mathcal{T}(n)$ consisting of functions which are, respectively, *starlike of order* α $(0 \leqq \alpha < 1)$ and *convex of order* α $(0 \leqq \alpha < 1)$ in $\mathbb{U}$. The classes $\mathcal{A}(n)$, $\mathcal{T}(n)$, $\mathcal{T}_\alpha(n)$, and $\mathcal{C}_\alpha(n)$ were investigated by Chatterjea [1] (and Srivastava *et al.* [9]). In particular, the following subclasses:

$$\mathcal{T} := \mathcal{T}(1), \quad \mathcal{T}^*(\alpha) := \mathcal{T}_\alpha(1), \quad \text{and} \quad \mathcal{C}(\alpha) := \mathcal{C}_\alpha(1)$$

were considered earlier by Silverman [7].

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Next, following the work of Sekine and Owa [4], we denote by $\mathcal{A}(n, \vartheta)$ the subclass of $\mathcal{A}$ consisting of all functions $f(z)$ of the form:

$$(1.1) \qquad f(z) = z - \sum_{k=n+1}^{\infty} e^{i(k-1)\vartheta} a_k z^k \quad (\vartheta \in \mathbb{R};\ a_k \geqq 0;\ n \in \mathbb{N}).$$

Finally, the subclasses $\mathcal{T}(n, \vartheta)$, $\mathcal{T}_\alpha^*(n, \vartheta)$, and $\mathcal{C}_\alpha(n, \vartheta)$ of the class $\mathcal{A}(n, \vartheta)$ are defined in the same way as the subclasses $\mathcal{T}(n)$, $\mathcal{T}_\alpha(n)$, and $\mathcal{C}_\alpha(n)$ of the class $\mathcal{A}(n)$.

We begin by recalling the following useful characterizations of the function classes $\mathcal{T}_\alpha^*(n, \vartheta)$ and $\mathcal{C}_\alpha(n, \vartheta)$ (see Sekine and Owa [4]).
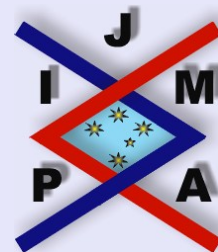
Lemma 1.1. *A function* $f(z) \in \mathcal{A}(n, \vartheta)$ *of the form* (1.1) *is in the class* $\mathcal{T}_\alpha^*(n, \vartheta)$ *if and only if*

$$(1.2) \qquad \sum_{k=n+1}^{\infty} (k - \alpha)\, a_k \leqq 1 - \alpha \quad (n \in \mathbb{N};\ 0 \leqq \alpha < 1).$$

Lemma 1.2. *A function* $f(z) \in \mathcal{A}(n, \vartheta)$ *of the form* (1.1) *is in the class* $\mathcal{C}_\alpha(n, \vartheta)$ *if and only if*

$$(1.3) \qquad \sum_{k=n+1}^{\infty} k\,(k - \alpha)\, a_k \leqq 1 - \alpha \quad (n \in \mathbb{N};\ 0 \leqq \alpha < 1).$$

Motivated by the equalities in (1.2) and (1.3) above, Sekine *et al.* [6] defined a general subclass $\mathcal{A}(n; B_k, \vartheta)$ of the class $\mathcal{A}(n, \vartheta)$ consisting of functions $f(z)$

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of the form (1.1), which satisfy the following inequality:

$$\sum_{k=n+1}^{\infty} B_k a_k \leqq 1 \quad (B_k > 0;\ n \in \mathbb{N}).$$

Thus it is easy to verify each of the following classifications and relationships:

$$\mathcal{A}(n; k, \vartheta) = \mathcal{T}_0^*(n, \vartheta) =: \mathcal{T}^*(n, \vartheta) = \mathcal{T}(n, \vartheta),$$

$$\mathcal{A}\left(n; \frac{k - \alpha}{1 - \alpha}, \vartheta\right) = \mathcal{T}_\alpha^*(n, \vartheta) \quad (0 \leqq \alpha < 1),$$

and

$$\mathcal{A}\left(n; \frac{k(k - \alpha)}{1 - \alpha}, \vartheta\right) = \mathcal{C}_\alpha(n, \vartheta) \quad (0 \leqq \alpha < 1).$$

As a matter of fact, Sekine *et al.* [6] also obtained each of the following basic properties of the general classes $\mathcal{A}(n; B_k, \vartheta)$.

Theorem 1.3. $\mathcal{A}(n; B_k, \vartheta)$ *is the convex subfamily of the class* $\mathcal{A}(n, \vartheta)$.

Theorem 1.4. *Let*

$$(1.4) \qquad f_1(z) = z \quad and \quad f_k(z) = z - \frac{e^{i(k-1)\vartheta}}{B_k} z^k$$

$$(k = n + 1, n + 2, n + 3, \ldots;\ n \in \mathbb{N}).$$

Then $f \in \mathcal{A}(n; B_k, \vartheta)$ *if and only if* $f(z)$ *can be expressed as follows:*

$$f(z) = \lambda_1 f_1(z) + \sum_{k=n+1}^{\infty} \lambda_k f_k(z),$$

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where

$$\lambda_1 + \sum_{k=n+1}^{\infty} \lambda_k = 1 \quad (\lambda_1 \geqq 0;\ \lambda_k \geqq 0;\ n \in \mathbb{N}).$$

Corollary 1.5. *The extreme points of the class* $\mathcal{A}(n; B_k, \vartheta)$ *are the functions* $f_1(z)$ *and* $f_k(z)$ $(k \geqq n+1;\ n \in \mathbb{N})$ *given by* (1.4).

Applying the concepts of extreme points, fractional calculus, and subordination, Sekine *et al.* [6] obtained several integral means inequalities for higher-order fractional derivatives and fractional integrals of functions belonging to the general classes $\mathcal{A}(n; B_k, \vartheta)$. Subsequently, Sekine and Owa [5] discussed the weakening of the hypotheses for B_k in those results by Sekine *et al.* [6]. In this paper, we investigate the integral means inequalities for the fractional derivatives of $f(z)$ of a general order $p + \lambda$ $(0 \leqq p \leqq n;\ 0 \leqq \lambda < 1)$ of functions $f(z)$ belonging to the general classes $\mathcal{A}(n; B_k, \vartheta)$.

We shall make use of the following definitions of fractional derivatives (*cf.* Owa [3]; see also Srivastava and Owa [8]).

Definition 1.1. *The fractional derivative of order* λ *is defined, for a function* $f(z)$, *by*

$$(1.5) \qquad D_z^\lambda f(z) := \frac{1}{\Gamma(1-\lambda)} \frac{d}{dz} \int_0^z \frac{f(\zeta)}{(z-\zeta)^\lambda}\, d\zeta \quad (0 \leqq \lambda < 1),$$

where the function $f(z)$ *is analytic in a simply-connected region of the complex* z-*plane containing the origin and the multiplicity of* $(z-\zeta)^{-\lambda}$ *is removed by requiring* $\log(z-\zeta)$ *to be real when* $z - \zeta > 0$.
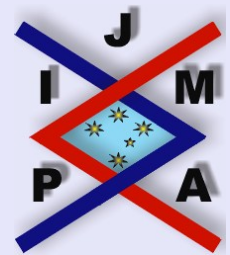
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Definition 1.2. *Under the hypotheses of Definition 1.1, the fractional derivative of order $n + \lambda$ is defined, for a function $f(z)$, by*

$$D_z^{n+\lambda} f(z) := \frac{d^n}{dz^n} D_z^\lambda f(z) \quad (0 \leqq \lambda < 1; \; n \in \mathbb{N}_0 := \mathbb{N} \cup \{0\}).$$

It readily follows from (1.5) in Definition 1.1 that

$$(1.6) \qquad D_z^\lambda z^k = \frac{\Gamma(k+1)}{\Gamma(k-\lambda+1)} z^{k-\lambda} \quad (0 \leqq \lambda < 1).$$

We shall also need the concept of subordination between analytic functions and a subordination theorem of Littlewood [2] in our investigation.

Given two functions $f(z)$ and $g(z)$, which are analytic in $\mathbb{U}$, the function $f(z)$ is said to be *subordinate* to $g(z)$ in $\mathbb{U}$ if there exists a function $w(z)$, analytic in $\mathbb{U}$ with

$$w(0) = 0 \quad \text{and} \quad |w(z)| < 1 \quad (z \in \mathbb{U}),$$

such that

$$f(z) = g(w(z)) \quad (z \in \mathbb{U}).$$
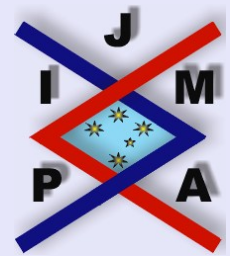
We denote this subordination by

$$f(z) \prec g(z).$$

Theorem 1.6 (Littlewood [2]). *If the functions $f(z)$ and $g(z)$ are analytic in $\mathbb{U}$ with*

$$g(z) \prec f(z),$$

then

$$\int_0^{2\pi} \left| g\left(re^{i\theta}\right) \right|^\mu d\theta \leqq \int_0^{2\pi} \left| f\left(re^{i\theta}\right) \right|^\mu d\theta \quad (\mu > 0; \; 0 < r < 1).$$

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2. The Main Integral Means Inequalities

Theorem 2.1. *Suppose that $f(z) \in \mathcal{A}\left(n; k^{p+1}B_k, \vartheta\right)$ and that*

$$\frac{(h+1)^q B_{h+1} \Gamma(h+2-\lambda-p)}{\Gamma(h+1)} \cdot \frac{\Gamma(n+1-p)}{\Gamma(n+2-\lambda-p)} \leqq B_k \quad (k \geqq n+1)$$

for some $h \geqq n$, $0 \leqq \lambda < 1$, and $0 \leqq q \leqq p \leqq n$. Also let the function $f_{h+1}(z)$ be defined by
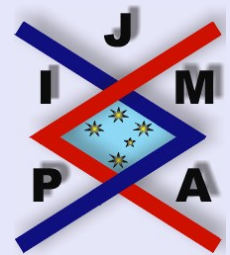
$$(2.1) \quad f_{h+1}(z) = z - \frac{e^{ih\vartheta}}{(h+1)^{q+1}B_{h+1}} z^{h+1} \quad \left(f_{h+1} \in A\left(n; k^{q+1}B_k, \vartheta\right)\right).$$

Then, for $z = re^{i\theta}$ and $0 < r < 1$,

$$(2.2) \quad \int_0^{2\pi} \left|D_z^{p+\lambda} f(z)\right|^\mu d\theta$$

$$\leqq \int_0^{2\pi} \left|D_z^{p+\lambda} f_{h+1}(z)\right|^\mu d\theta \qquad (0 \leqq \lambda < 1; \ \mu > 0).$$

Proof. By virtue of the fractional derivative formula (1.6) and Definition 1.2, we find from (1.1) that

$$D_z^{p+\lambda} f(z)$$

$$= \frac{z^{1-\lambda-p}}{\Gamma(2-\lambda-p)} \left(1 - \sum_{k=n+1}^\infty e^{i(k-1)\vartheta} \frac{\Gamma(2-\lambda-p)\Gamma(k+1)}{\Gamma(k+1-\lambda-p)} a_k \, z^{k-1}\right)$$

$$= \frac{z^{1-\lambda-p}}{\Gamma(2-\lambda-p)} \left(1 - \sum_{k=n+1}^\infty e^{i(k-1)\vartheta} \Gamma(2-\lambda-p) \frac{k!}{(k-p-1)!} \Phi(k) a_k z^{k-1}\right),$$

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where

(2.3) $\qquad \Phi(k) := \dfrac{\Gamma(k-p)}{\Gamma(k+1-\lambda-p)} \qquad (0 \leqq \lambda < 1;\ k \geqq n+1;\ n \in \mathbb{N}).$

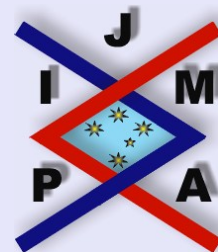Since $\Phi(k)$ is a *decreasing* function of k, we have

$$0 < \Phi(k) \leqq \Phi(n+1) = \frac{\Gamma(n+1-p)}{\Gamma(n+2-\lambda-p)}$$
$$(0 \leqq \lambda < 1;\ k \geqq n+1;\ n \in \mathbb{N}).$$

Similarly, from (2.1), (1.6), and Definition 1.2, we obtain, for $0 \leqq \lambda < 1$,

$$D_z^{p+\lambda} f_{h+1}(z)$$
$$= \frac{z^{1-\lambda-p}}{\Gamma(2-\lambda-p)} \left(1 - \frac{e^{ih\vartheta}}{(h+1)^{q+1} B_{h+1}} \cdot \frac{\Gamma(2-\lambda-p)\Gamma(h+2)}{\Gamma(h+2-\lambda-p)}\, z^h \right).$$

For $z = re^{i\theta}$ and $0 < r < 1$, we must show that

$$\int_0^{2\pi} \left| 1 - \sum_{k=n+1}^{\infty} e^{i(k-1)\vartheta}\Gamma(2-\lambda-p)\frac{k!}{(k-p-1)!}\,\Phi(k) a_k z^{k-1} \right|^\mu d\theta$$
$$\leqq \int_0^{2\pi} \left| 1 - \frac{e^{ih\vartheta}}{(h+1)^{q+1} B_{h+1}} \cdot \frac{\Gamma(2-\lambda-p)\Gamma(h+2)}{\Gamma(h+2-\lambda-p)}\, z^h \right|^\mu d\theta,$$
$$(0 \leqq \lambda < 1;\ \mu > 0).$$

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Thus, by applying Theorem 1.6, it would suffice to show that

$$(2.4) \quad 1 - \sum_{k=n+1}^{\infty} e^{i(k-1)\vartheta} \Gamma(2-\lambda-p) \frac{k!}{(k-p-1)!} \Phi(k) a_k z^{k-1}$$

$$\prec 1 - \frac{e^{ih\vartheta}}{(h+1)^{q+1} B_{h+1}} \cdot \frac{\Gamma(2-\lambda-p)\Gamma(h+2)}{\Gamma(h+2-\lambda-p)} z^h.$$

Indeed, by setting

$$1 - \sum_{k=n+1}^{\infty} e^{i(k-1)\vartheta} \Gamma(2-\lambda-p) \frac{k!}{(k-p-1)!} \Phi(k) a_k z^{k-1}$$

$$= 1 - \frac{e^{ih\vartheta}}{(h+1)^{q+1} B_{h+1}} \cdot \frac{\Gamma(2-\lambda-p)\Gamma(h+2)}{\Gamma(h+2-\lambda-p)} \{w(z)\}^h,$$
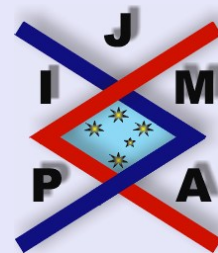
we find that

$$\{w(z)\}^h = \frac{(h+1)^{q+1} B_{h+1} \Gamma(h+2-\lambda-p)}{e^{ih\vartheta} \Gamma(h+2)}$$

$$\times \sum_{k=n+1}^{\infty} e^{i(k-1)\vartheta} \frac{k!}{(k-p-1)!} \Phi(k) a_k z^{k-1},$$

which readily yields $w(0) = 0$.

Therefore, we have

$$|w(z)|^h \leqq \frac{(h+1)^{q+1} B_{h+1} \Gamma(h+2-\lambda-p)}{\Gamma(h+2)} \sum_{k=n+1}^{\infty} \frac{k!}{(k-p-1)!} \Phi(k) a_k |z|^{k-1}$$

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$$\leqq |z|^n \frac{(h+1)^{q+1} B_{h+1} \Gamma(h+2-\lambda-p)}{\Gamma(h+2)}$$

$$\times \Phi(n+1) \sum_{k=n+1}^{\infty} \frac{k!}{(k-p-1)!} a_k$$

$$= |z|^n \frac{(h+1)^{q+1} B_{h+1} \Gamma(h+2-\lambda-p)}{\Gamma(h+2)}$$

$$\times \frac{\Gamma(n+1-p)}{\Gamma(n+2-\lambda-p)} \sum_{k=n+1}^{\infty} \frac{k!}{(k-p-1)!} a_k$$

$$= |z|^n \frac{(h+1)^{q} B_{h+1} \Gamma(h+2-\lambda-p)}{\Gamma(h+1)}$$

$$\times \frac{\Gamma(n+1-p)}{\Gamma(n+2-\lambda-p)} \sum_{k=n+1}^{\infty} \frac{k!}{(k-p-1)!} a_k$$

$$\leqq |z|^n \sum_{k=n+1}^{\infty} \frac{k!}{(k-p-1)!} B_k a_k$$

$$(2.5) \qquad \leqq |z|^n \sum_{k=n+1}^{\infty} k^{p+1} B_k a_k \leqq |z|^n < 1 \quad (n \in \mathbb{N}),$$

by means of the hypothesis of Theorem 2.1.

In light of the last inequality in (2.5) above, we have the subordination (2.4), which evidently proves Theorem 2.1. $\qquad \square$

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3. Remarks and Observations

First of all, in its special case when $p = q = 0$, Theorem 2.1 readily yields

Corollary 3.1 (cf. Sekine and Owa [5], Theorem 6). *Suppose that* $f(z) \in \mathcal{A}(n; kB_k, \vartheta)$ *and that*

$$\frac{B_{h+1}\Gamma(h+2-\lambda)}{\Gamma(h+1)} \cdot \frac{\Gamma(n+1)}{\Gamma(n+2-\lambda)} \leqq B_k \quad (k \geqq n+1; \ n \in \mathbb{N})$$

for some $h \geqq n$ *and* $0 \leqq \lambda < 1$. *Also let the function* $f_{h+1}(z)$ *be defined by*

$$(3.1) \qquad f_{h+1}(z) = z - \frac{e^{ih\vartheta}}{(h+1)B_{h+1}} \, z^{h+1} \quad (f_{h+1} \in \mathcal{A}(n; kB_k, \vartheta)).$$

Then, for $z = re^{i\theta}$ *and* $0 < r < 1$,

$$(3.2) \quad \int_0^{2\pi} \left| D_z^\lambda f(z) \right|^\mu d\theta \leqq \int_0^{2\pi} \left| D_z^\lambda f_{h+1}(z) \right|^\mu d\theta \quad (0 \leqq \lambda < 1; \ \mu > 0).$$
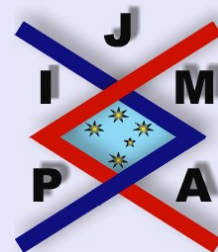
A *further* consequence of Corollary 3.1 when $h = n$ would lead us immediately to Corollary 3.2 below.

Corollary 3.2. *Suppose that* $f(z) \in \mathcal{A}(n; kB_k, \vartheta)$ *and that*

$$(3.3) \qquad\qquad B_{n+1} \leqq B_k \quad (k \geqq n+1; \ n \in \mathbb{N}).$$

Also let the function $f_{n+1}(z)$ *be defined by*

$$f_{n+1}(z) = z - \frac{e^{in\vartheta}}{(n+1)B_{n+1}} \, z^{n+1} \quad (f_{h+1} \in \mathcal{A}(n; kB_k, \vartheta)).$$

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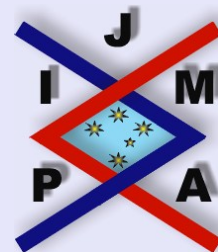Title Page

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Then, for $z = re^{i\theta}$ and $0 < r < 1$,

$$(3.4) \quad \int_0^{2\pi} \left| D_z^\lambda f(z) \right|^\mu d\theta \leqq \int_0^{2\pi} \left| D_z^\lambda f_{n+1}(z) \right|^\mu d\theta \quad (0 \leqq \lambda < 1; \ \mu > 0).$$

The hypothesis (3.3) in Corollary 3.2 is weaker than the corresponding hypothesis in an earlier result of Sekine *et al.* [6, p. 953, Theorem 6].

Next, for $p = 1$ and $q = 0$, Theorem 2.1 reduces to an integral means inequality of Sekine and Owa [5, Theorem 7] which, for $h = n$, yields another result of Sekine *et al.* [6, p. 953, Theorem 7] under weaker hypothesis as mentioned above.

Finally, by setting $p = q = 1$ in Theorem 2.1, we obtain a slightly improved version of another integral means inequalities of Sekine and Owa [5, Theorem 8] with respect to the parameter λ (see also Sekine *et al.* [6, p. 955, Theorem 8] for the case when $h = n$, just as we remarked above).

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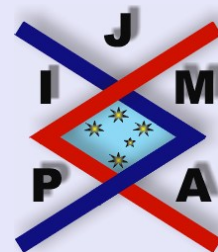
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