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*Research Article*

# Starlikeness Properties of a New Integral Operator for Meromorphic Functions

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We define here an integral operator $\mathscr{H}_{\gamma_1,\ldots,\gamma_n}$ for meromorphic functions in the punctured open unit disk. Several starlikeness conditions for the integral operator $\mathscr{H}_{\gamma_1,\ldots,\gamma_n}$ are derived.

## 1. Introduction

Let $\Sigma$ denotes the class of functions of the form

$$f(z) = \frac{1}{z} + \sum_{n=0}^{\infty} a_n z^n, \tag{1.1}$$

which are analytic in the punctured open unit disk

$$\mathbb{U}^* = \{z \in \mathbb{C} : \ 0 < |z| < 1\} = \mathbb{U} \setminus \{0\}, \tag{1.2}$$

where $\mathbb{U}$ is the open unit disk $\mathbb{U} = \{z \in \mathbb{C} : |z| < 1\}$.

We say that a function $f \in \Sigma$ is meromorphic starlike of order $\alpha$ $(0 \leq \alpha < 1)$, and belongs to the class $\Sigma^*(\alpha)$, if it satisfies the inequality

$$-\Re\left(\frac{zf'(z)}{f(z)}\right) > \alpha. \tag{1.3}$$

A function $f \in \Sigma$ is a meromorphic convex function of order $\alpha$ $(0 \le \alpha < 1)$, if $f$ satisfies the following inequality

$$-\Re\left(1 + \frac{zf''(z)}{f'(z)}\right) > \alpha, \tag{1.4}$$

and we denote this class by $\Sigma_k(\alpha)$.

Analogous to the integral operator defined by Breaz et al. [1] on the normalized analytic functions, we now define the following integral operator on the space meromorphic functions in the class $\sum$.

*Definition 1.1.* Let $n \in \mathbb{N}$, $\gamma_i > 0$, $i \in \{1, 2, 3, \ldots, n\}$. We define the integral operator $\mathscr{H}_{\gamma_1,\ldots,\gamma_n}(f_1, f_2, \ldots, f_n) : \Sigma^n \to \Sigma$ by

$$\mathscr{H}_{\gamma_1,\ldots,\gamma_n}(f_1, \ldots, f_n)(z) = \frac{1}{z^2}\int_0^z \left(-u^2 f_1'(u)\right)^{\gamma_1} \cdots \left(-u^2 f_n'(u)\right)^{\gamma_n} du. \tag{1.5}$$

For the sake of simplicity, from now on we will write $\mathscr{H}_{\gamma_1,\ldots,\gamma_n}(z)$ instead of $\mathscr{H}_{\gamma_1,\ldots,\gamma_n}(f_1, \ldots, f_n)(z)$.

By $\Sigma_{k_p}(\beta)$ $(-1 \le \beta < 1)$, we denote the class of functions $f \in \Sigma$ such that

$$\left|\frac{zf''(z)}{f'(z)} + 2\right| < -\Re\left(\frac{zf''(z)}{f'(z)} + \beta\right) - 1. \tag{1.6}$$

In order to derive our main results, we have to recall here the following preliminary results.

**Lemma 1.2** (see [2]). *Suppose that the function $\Psi : \mathbb{C}^2 \to \mathbb{C}$ satisfies the following condition:*

$$\Re\{\Psi(is, t)\} \le 0, \quad \left(s, t \in \mathbb{R};\ \ t \le \frac{-(1+s^2)}{2}\right). \tag{1.7}$$

*If the function $p(z) = 1 + p_1 z + \cdots$ is analytic in $\mathbb{U}$ and*

$$\Re\{\Psi(p(z), zp'(z))\} > 0, \quad (z \in \mathbb{U}), \tag{1.8}$$

*then,*

$$\Re\{p(z)\} > 0 \quad (z \in \mathbb{U}). \tag{1.9}$$

**Proposition 1.3** (see [3]). *If $f \in \Sigma$ satisfying*

$$\begin{gathered} -\Re\left\{\frac{z(zf''(z) + 3f'(z))}{zf'(z) + 2f(z)}\right\} > \alpha, \quad 0 \le \alpha < 1, \\ \left|\frac{zf'(z)}{f(z)} + 1\right| < 1, \end{gathered} \tag{1.10}$$

*then,*

$$-\Re\left\{\frac{zf'(z)}{f(z)}\right\} > \alpha. \tag{1.11}$$

## 2. Starlikeness of the Operator $\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)$

In this section, we investigate sufficient conditions for the integral operator $\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)$ which is defined in Definition 1.1, to be in the class $\Sigma^*(\alpha)$, $0 \le \alpha < 1$.

**Theorem 2.1.** *Let $f_i \in \sum$, $\gamma_i > 0$ for all $i \in \{1,\ldots,n\}$. If*

$$-\Re\left(\frac{zf_i''(z)}{f_i'(z)}\right) > \frac{-1}{n\gamma_i} + 2, \tag{2.1}$$

*then $\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)$ belongs to $\Sigma^*(0)$.*

*Proof.* On successive differentiation of $\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)$, which is defined in (1.5), we get

$$\begin{aligned}
&2z\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z) + z^2\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z) = \left(-z^2 f_1'(z)\right)^{\gamma_1}\cdots\left(-z^2 f_n'(z)\right)^{\gamma_n},\\
&z^2\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z) + 4z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z) + 2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)\\
&\quad = \sum_{i=1}^{n}\gamma_i\left(-z^2 f_i'(z)\right)^{\gamma_i-1}\left(-z^2 f_i''(z) - 2zf_i'(z)\right)\prod_{j=1,j\neq i}^{n}\left(-z^2 f_j'(z)\right)^{\gamma_j}.
\end{aligned} \tag{2.2}$$

Then from (2.2), we obtain

$$\frac{z^2\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z) + 4z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z) + 2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}{z^2\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z) + 2z\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)} = \sum_{i=1}^{n}\gamma_i\left(\frac{f_i''(z)}{f_i'(z)} + \frac{2}{z}\right). \tag{2.3}$$

By multiplying (2.3) with $z$ yield,

$$\frac{z^2\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z) + 4z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z) + 2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z) + 2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)} = \sum_{i=1}^{n}\gamma_i\left(\frac{zf_i''(z)}{f_i'(z)} + 2\right). \tag{2.4}$$

That is equivalent to

$$\left\{\frac{z\left(z\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z) + 3\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)\right)}{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z) + 2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}\right\} + 1 = \sum_{i=1}^{n}\gamma_i\left(\frac{zf_i''(z)}{f_i'(z)} + 2\right). \tag{2.5}$$

Or

$$-\left\{\frac{z\left(z\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z)+3\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)\right)}{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)+2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}\right\}=\sum_{i=1}^{n}\gamma_i\left(-\frac{zf_i''(z)}{f_i'(z)}\right)-2\sum_{i=1}^{n}\gamma_i+1. \tag{2.6}$$

We can write the left-hand side of (2.6), as the following:

$$\begin{aligned}&\frac{-\left(z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)/\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)\right)\left(\left(z\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z)/\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)\right)+3\right)}{\left(z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)/\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)\right)+2}\\&\quad=\sum_{i=1}^{n}\gamma_i\left(-\frac{zf_i''(z)}{f_i'(z)}\right)-2\sum_{i=1}^{n}\gamma_i+1.\end{aligned} \tag{2.7}$$

We define the regular function $p$ in $\mathbb{U}$ by

$$p(z)=-\frac{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)}{\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}, \tag{2.8}$$

and $p(0)=1$. Differentiating $p(z)$ logarithmically, we obtain

$$-p(z)+\frac{zp'(z)}{p(z)}=1+\frac{z\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z)}{\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)}. \tag{2.9}$$

From (2.7), (2.8), and (2.9), we obtain

$$p(z)+\frac{zp'(z)}{-p(z)+2}=\sum_{i=1}^{n}\gamma_i\left(-\frac{zf_i''(z)}{f_i'(z)}\right)-2\sum_{i=1}^{n}\gamma_i+1. \tag{2.10}$$

Let us put

$$\Psi(u,v)=u+\frac{v}{-u+2}. \tag{2.11}$$

From (2.1), (2.10), and (2.11), we obtain

$$\begin{aligned}\Re\{\Psi(p(z),zp'(z))\}&=\gamma_1\left(-\Re\frac{zf_1''(z)}{f_1'(z)}\right)+\cdots+\left(-\Re\frac{zf_n''(z)}{f_n'(z)}\right)-2(\gamma_1+\cdots+\gamma_n)+1\\&>\gamma_1\left(\frac{-1}{n\gamma_1}+2\right)+\cdots+\gamma_n\left(\frac{-1}{n\gamma_n}+2\right)-2(\gamma_1+\cdots+\gamma_n)+1=0.\end{aligned} \tag{2.12}$$

Now, we proceed to show that

$$\Re\{\Psi(is,t)\} \leq 0, \quad \left(s,t \in \mathbb{R}; t \leq \frac{-(1+s^2)}{2}\right). \tag{2.13}$$

Indeed, from (2.11), we have

$$\Re\{\Psi(is,t)\} = \Re\left\{is + \frac{t}{-is+2}\right\} = \frac{2t}{4+s^2} \leq -\frac{1+s^2}{4+s^2} < 0. \tag{2.14}$$

Thus, from (2.12), (2.14), and by using Lemma 1.2, we conclude that $\Re\{p(z)\} > 0$, and so

$$-\Re\left\{\frac{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)}{\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}\right\} > 0 \tag{2.15}$$

that is, $\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)$ is starlike of order 0. □

**Theorem 2.2.** *For $i \in \{1,\ldots,n\}$, let $\gamma_i > 0$ and $f_i \in \Sigma_k(\alpha_i)$ $(0 \leq \alpha_i < 1)$. If $0 < \sum_{i=1}^{n} \gamma_i(1-\alpha_i) \leq 1$, $\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)$ be the integral operator given by* (1.5) *and*

$$\left|\frac{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)}{\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)} + 1\right| < 1. \tag{2.16}$$

*Then $\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)$ belong to $\Sigma^*(\mu)$, where $\mu = 1 - \sum_{i=1}^{n} \gamma_i(1-\alpha_i)$.*

*Proof.* Following the same steps as in Theorem 2.1, we obtain

$$-\left\{\frac{z\left(z\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z) + 3\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)\right)}{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z) + 2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}\right\} = \sum_{i=1}^{n}\gamma_i\left\{-\left(\frac{zf_i''(z)}{f_i'(z)} + 1\right)\right\} + 1 - \sum_{i=1}^{n}\gamma_i. \tag{2.17}$$

Taking the real part of both terms of the last expression, we have

$$-\Re\left\{\frac{z\left(z\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z) + 3\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)\right)}{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z) + 2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}\right\} = \sum_{i=1}^{n}\gamma_i\left\{-\Re\left(\frac{zf_i''(z)}{f_i'(z)} + 1\right)\right\} + 1 - \sum_{i=1}^{n}\gamma_i. \tag{2.18}$$

Since $f_i \in \Sigma_k(\alpha_i)$, for $i \in \{1, \ldots, n\}$, we receive

$$-\Re\left\{\frac{z\left(z\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z) + 3\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)\right)}{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z) + 2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}\right\} > \sum_{i=1}^{n}\gamma_i\alpha_i + 1 - \sum_{i=1}^{n}\gamma_i. \tag{2.19}$$

Therefore,

$$-\Re\left\{\frac{z\left(z\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z) + 3\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)\right)}{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z) + 2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}\right\} > 1 - \sum_{i=1}^{n}\gamma_i(1-\alpha_i). \tag{2.20}$$

Using (2.16), (2.20), and applying Proposition 1.3, we get $\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z) \in \Sigma^*(\mu)$, where $\mu = 1 - \sum_{i=1}^{n}\gamma_i(1-\alpha_i)$. □

Letting $\alpha_i = \alpha$, $i \in \{1, \ldots, n\}$ in Theorem 2.2, we get the following.

**Corollary 2.3.** *For $i \in \{1, \ldots, n\}$, let $\gamma_i > 0$ and $f_i \in \Sigma_k(\alpha)$ $(0 \le \alpha < 1)$. If*

$$0 < \sum_{i=1}^{n}\gamma_i \le \frac{1}{1-\alpha}, \tag{2.21}$$

*$\mathcal{H}_{\gamma_1,\ldots,\gamma_n}$ be the integral operator given by* (1.5) *and*

$$\left|\frac{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)}{\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)} + 1\right| < 1. \tag{2.22}$$

*Then $\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)$ is starlike of order $1 - (1-\alpha)\sum_{i=1}^{n}\gamma_i$.*

**Theorem 2.4.** *For $i \in \{1, \ldots, n\}$, let $\gamma_i > 0$ and $f_i \in \Sigma_{k_p}(\beta_i)$ $(-1 \le \beta_i < 1)$. If*

$$0 < \sum_{i=1}^{n}\gamma_i(1-\beta_i) \le 1, \tag{2.23}$$

*$\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)$ be the integral operator given by* (1.5) *and*

$$\left|\frac{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)}{\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)} + 1\right| < 1. \tag{2.24}$$

*Then $\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)$ is starlike of order $1 - \sum_{i=1}^{n}\gamma_i(1-\beta_i)$.*

*Proof.* Following the same steps as in Theorem 2.1, we obtain

$$\begin{aligned}
-\left\{\frac{z\left(z\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z)+3\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)\right)}{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)+2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}\right\} &= -\sum_{i=1}^{n}\gamma_i\left(\frac{zf_i''(z)}{f_i'(z)}+2\right)+1 \\
&= \sum_{i=1}^{n}\gamma_i\left\{-\left(\frac{zf_i''(z)}{f_i'(z)}+\beta_i\right)-1\right\}+1-\sum_{i=1}^{n}\gamma_i+\sum_{i=1}^{n}\gamma_i\beta_i \\
&= \sum_{i=1}^{n}\gamma_i\left\{-\left(\frac{zf_i''(z)}{f_i'(z)}+\beta_i\right)-1\right\}+1-\sum_{i=1}^{n}\gamma_i(1-\beta_i).
\end{aligned} \tag{2.25}$$

We calculate the real part from both terms of the above equality and obtain

$$\begin{aligned}
&-\Re\left\{\frac{z\left(z\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z)+3\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)\right)}{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)+2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}\right\} \\
&\quad= \sum_{i=1}^{n}\gamma_i\left\{-\Re\left(\frac{zf_i''(z)}{f_i'(z)}+\beta_i\right)-1\right\}+1-\sum_{i=1}^{n}\gamma_i(1-\beta_i).
\end{aligned} \tag{2.26}$$

Since $f_i \in \Sigma_{k_p}(\beta_i)$ for all $i \in \{1,\ldots,n\}$, the above relation then yields

$$\begin{aligned}
&-\Re\left\{\frac{z\left(z\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z)+3\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)\right)}{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)+2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}\right\} \\
&\quad> \sum_{i=1}^{n}\gamma_i\left|\frac{zf_i''(z)}{f_i'(z)}+2\right|+1-\sum_{i=1}^{n}\gamma_i(1-\beta_i).
\end{aligned} \tag{2.27}$$

Because $\sum_{i=1}^{n}\gamma_i|zf_i''(z)/f_i'(z)+2| \geq 0$, we obtain that

$$-\Re\left\{\frac{z\left(z\mathcal{H}''_{\gamma_1,\ldots,\gamma_n}(z)+3\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)\right)}{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)+2\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}\right\} > 1-\sum_{i=1}^{n}\gamma_i(1-\beta_i). \tag{2.28}$$

Using (2.24), (2.28) and applying Proposition 1.3, we get $\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)$ is a starlike function of order $1-\sum_{i=1}^{n}\gamma_i(1-\beta_i)$. □

Letting $\beta_i = \beta, i \in \{1,\ldots,n\}$ in Theorem 2.4, we get the following.

**Corollary 2.5.** *For $i \in \{1,\ldots,n\}$, let $\gamma_i > 0$ and $f_i \in \Sigma_{k_p}(\beta)$ $(-1 \leq \beta < 1)$. If*

$$0 < \sum_{i=1}^{n}\gamma_i \leq \frac{1}{1-\beta}, \tag{2.29}$$

*$\mathcal{H}_{\gamma_1,\ldots,\gamma_n}$ be the integral operator given by* (1.5) *and*

$$\left|\frac{z\mathcal{H}'_{\gamma_1,\ldots,\gamma_n}(z)}{\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)}+1\right|<1. \tag{2.30}$$

*Then $\mathcal{H}_{\gamma_1,\ldots,\gamma_n}(z)$ is starlike of order $1-(1-\beta)\sum_{i=1}^{n}\gamma_i$.*

Letting $n=1$, $\gamma_1=\gamma$ and $f_1=f$ in Corollary 2.5, we get the following.

**Corollary 2.6.** *Let $\gamma>0$, and $f\in\Sigma_{k_p}(\beta)$ $(-1\le\beta<1)$. If*

$$0<\gamma\le\frac{1}{1-\beta}, \tag{2.31}$$

*$\mathcal{H}_\gamma(z)$ be the integral operator,*

$$\begin{gathered}\mathcal{H}_\gamma(z)=\frac{1}{z^2}\int_0^z\left(-u^2f'(u)\right)^\gamma du,\\ \left|\frac{z\mathcal{H}'_\gamma(z)}{\mathcal{H}_\gamma(z)}+1\right|<1.\end{gathered} \tag{2.32}$$

*Then $\mathcal{H}_\gamma(z)$ is starlike of order $1-(1-\beta)\gamma$.*

Other work related to integral operator for different studies can also be found in [4–6].

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