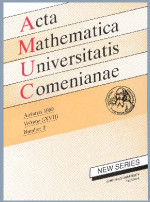

ON THE HILBERT INEQUALITY

ZHOU YU AND GAO MINGZHE

Abstract. In this paper it is shown that the Hilbert inequality for double series can be improved by introducing a weight function of the form $\frac{\sqrt{n}}{n+1}\left(\frac{\sqrt{n}-1}{\sqrt{n}+1}-\frac{\ln n}{\pi}\right)$, where $n\in N$. A similar result for the Hilbert integral inequality is also given. As applications, some sharp results of Hardy-Littlewood's theorem and Widder's theorem are obtained.

1. Introduction

Let $\{a_n\}$ and $\{b_n\}$ be two sequences of complex numbers. It is all-round known that the inequality

$$\left|\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\frac{a_m\bar{b}_n}{m+n}\right|^2\le\pi^2\sum_{n=1}^{\infty}|a_n|^2\sum_{n=1}^{\infty}|b_n|^2 \tag{1.1}$$

is called the Hilbert inequality for double series, where $\sum\limits_{n=1}^{\infty}|a_n|^2<+\infty$ and $\sum\limits_{n=1}^{\infty}|b_n|^2<+\infty$, and that the constant factor π^2 in (1.1) is the best possible. The equality in (1.1) holds if and only if

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$\{a_n\}$, or $\{b_n\}$ is a zero-sequence (see [2]). The corresponding integral form of (1.1) is that

$$\left|\int_0^\infty\int_0^\infty \frac{f(x)\bar{g}(y)}{x+y}\mathrm{d}x\mathrm{d}y\right|^2 \le \pi^2\left(\int_0^\infty |f(x)|^2\,\mathrm{d}x\right)\left(\int_0^\infty |g\left(x\right)|^2\,\mathrm{d}x\right) \tag{1.2}$$

where $\int\limits_0^\infty |f\left(x\right)|^2 \mathrm{d}x < +\infty$ and $\int\limits_0^\infty |g\left(x\right)|^2 \mathrm{d}x < +\infty$, and that the constant factor π^2 in (1.2) is also the best possible. The equality in (1.2) holds if and only if $f\left(x\right) = 0$, or $g\left(x\right) = 0$. Recently, various improvements and extensions of (1.1) and (1.2) appeared in a great deal of papers (see [2]). The purpose of the present paper is to build the Hilbert inequality with the weights by means of a monotonic function of the form $\frac{\sqrt{x}}{1+\sqrt{x}}$, thereby new refinements of (1.1) and (1.2) are established, and then to give some of their important applications.

For convenience, we need the following lemmas.

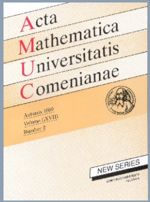
Lemma 1.1. *Let $n \in \mathbb{N}$. Then*

$$\int_0^\infty \frac{\mathrm{d}x}{(n+x^2)(1+x)} = \frac{1}{n+1}\left(\frac{\pi}{2\sqrt{n}} + \frac{1}{2}\ln n\right) \tag{1.3}$$

Proof. Let a, e and f be real numbers. Then

$$\begin{aligned}&\int \frac{\mathrm{d}x}{(a^2+x^2)(e+fx)}\\ &\quad = \frac{1}{e^2+a^2f^2}\left\{f\ln|e+fx| - \frac{1}{2}\ln(a^2+x^2) + \frac{e}{a}\arctan\frac{x}{a}\right\} + C\end{aligned}$$

where C is an arbitrary constant. This result has been given in the papers (see [3]–[4]). Based on this indefinite integral it is easy to deduce that the equality (1.3) is true. $\square$



Lemma 1.2. *Let $n \in \mathbb{N}$, $x \in (0, +\infty)$. Define two functions by*

$$f\,(x) = \left(\frac{1}{x+n}\left(\frac{n}{x}\right)^{\frac{1}{2}}\right)\left(1 - \left(\frac{\sqrt{x}}{1+\sqrt{x}} - \frac{\sqrt{n}}{1+\ \sqrt{n}}\right)\right)$$

$$g\,(x) = \left(\frac{1}{x+n}\left(\frac{n}{x}\right)^{\frac{1}{2}}\right)\left(1 + \left(\frac{\sqrt{x}}{1+\sqrt{x}} - \frac{\sqrt{n}}{1+\sqrt{n}}\right)\right),$$

then $f\,(x)$ and $g\,(x)$ are monotonously decreasing in $(0,\,+\,\infty)$, and

$$\int_0^\infty f\,(x)\,\mathrm{d}x = \pi - \pi\omega\,(n) \tag{1.4}$$

$$\int_0^\infty g\,(x)\,\mathrm{d}x = \pi + \pi\omega\,(n) \tag{1.5}$$

where the weight function ω is defined by

$$\omega\,(n) = \frac{\sqrt{n}}{n+1}\left(\frac{\sqrt{n}-1}{\sqrt{n}+1} - \frac{\ln n}{\pi}\right) \tag{1.6}$$

Proof. At first, notice that $1 - \frac{\sqrt{x}}{1+\sqrt{x}} = \frac{1}{1+\sqrt{x}}$, hence we can write $f\,(x)$ in form $f\,(x) = f_1\,(x) + f_2\,(x)$, where

$$f_1\,(x) = \left(\frac{1}{(x+n)\sqrt{x}}\right)\left(\frac{n}{1+\sqrt{n}}\right), \qquad f_2\,(x) = \frac{\sqrt{n}}{(x+n)\,(1+\sqrt{x})\,\sqrt{x}}.$$

It is obvious that $f_1\,(x)$ and $f_2\,(x)$ are monotonously decreasing in $(0,\,+\,\infty)$. Hence $f\,(x)$ is monotonously decreasing in $(0,\,+\infty\,)$. Next, notice that $1 - \frac{\sqrt{n}}{1+\sqrt{n}} = \frac{1}{1+\sqrt{n}}$, we can write $g\,(x)$ in form $g(x) = g_1(x) + g_2(x)$, where

$$g_1(x) = \frac{\sqrt{n}}{(1+\sqrt{n})(x+n)\sqrt{x}}, \qquad g_2(x) = \frac{\sqrt{n}}{(x+n)(1+\sqrt{x})}.$$

It is obvious that $g_1(x)$ and $g_2(x)$ are monotonously decreasing in $(0, +\infty)$. Hence $g(x)$ is also monotonously decreasing in $(0, +\infty)$. Further we need only to compute two integrals.

$$\begin{aligned}
\int_0^\infty f(x)\,\mathrm{d}x &= \int_0^\infty \left(\frac{1}{x+n}\left(\frac{n}{x}\right)^{\frac{1}{2}}\right)\left(1+\frac{\sqrt{n}}{1+\sqrt{n}}-\frac{\sqrt{x}}{1+\sqrt{x}}\right)\mathrm{d}x \\
&= \left(1+\frac{\sqrt{n}}{1+\sqrt{n}}\right)\int_0^\infty\left(\frac{1}{x+n}\left(\frac{n}{x}\right)^{\frac{1}{2}}\right)\mathrm{d}x-\int_0^\infty\left(\frac{1}{x+n}\left(\frac{n}{x}\right)^{\frac{1}{2}}\right)\left(\frac{\sqrt{x}}{1+\sqrt{x}}\right)\mathrm{d}x \\
&= \left(1+\frac{\sqrt{n}}{1+\sqrt{n}}\right)\pi-\int_0^\infty\left(\frac{1}{x+n}\left(\frac{n}{x}\right)^{\frac{1}{2}}\right)\left(\frac{\sqrt{x}}{1+\sqrt{x}}\right)\mathrm{d}x \\
&= \pi-\left\{2\sqrt{n}\left(\int_0^\infty\frac{1}{(n+t^2)}\mathrm{d}t-\int_0^\infty\frac{1}{(n+t^2)(1+t)}\mathrm{d}t\right)-\frac{\sqrt{n}\,\pi}{1+\sqrt{n}}\right\} \\
&= \pi-\left\{\pi-2\sqrt{n}\int_0^\infty\frac{1}{(n+t^2)(1+t)}\mathrm{d}t-\frac{\sqrt{n}\,\pi}{1+\sqrt{n}}\right\}
\end{aligned}$$

By Lemma 1.1, we obtain

$$\int_0^\infty f(x)\,\mathrm{d}x = \pi - \left\{\pi - \left(\frac{\pi}{n+1} + \frac{\sqrt{n}\ln n}{n+1}\right) - \frac{\sqrt{n}\,\pi}{1+\sqrt{n}}\right\} \tag{1.7}$$

The equality (1.4) follows from (1.7) at once after some simple computations and simplifications. Similarly, the equality (1.5) can be obtained.

□

2. Main Results

First, we establish a new refinement of (1.1).

Theorem 2.1. *Let $\{a_n\}$ and $\{b_n\}$ be two sequences of complex numbers. If $\sum\limits_{n=1}^{\infty} |a_n|^2 < +\infty$ and $\sum\limits_{n=1}^{\infty} |b_n|^2 < +\infty$, then*

$$\begin{aligned}\left|\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{a_m\bar{b}_n}{m+n}\right|^4 &\le \pi^4\left\{\left(\sum_{n=1}^{\infty}|a_n|^2\right)^2 - \left(\sum_{n=1}^{\infty}\omega(n)|a_n|^2\right)^2\right\}\\ &\quad\times\left\{\left(\sum_{n=1}^{\infty}|b_n|^2\right)^2 - \left(\sum_{n=1}^{\infty}\omega(n)|b_n|^2\right)^2\right\}\end{aligned} \tag{2.1}$$

where the weight function $\omega(n)$ is defined by (1.6).

Proof. Let $c(x)$ be a real function and satisfy the condition $1 - c\,(n) + c\,(m) \geq 0$, $(n, m \in N)$. Firstly we suppose that $b_n = a_n$. Applying Cauchy's inequality we have

$$
\begin{aligned}
\left| \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{a_m \bar{a}_n}{m+n} \right|^2 &= \left| \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{a_m \bar{a}_n}{m+n} \left(1 - c\,(n) + c\,(m)\right) \right|^2 \\
&= \left| \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \left(\frac{a_m \left(1 - c(n) + c(m)\right)^{1/2}}{(m+n)^{1/2}} \left(\frac{m}{n}\right)^{1/4} \right) \right. \\
&\qquad \left. \times \left(\frac{\bar{a}_n \left(1 - c(n) + c(m)\right)^{1/2}}{(m+n)^{1/2}} \left(\frac{n}{m}\right)^{1/4} \right) \right|^2 \\
&\leq J_1 J_2 \qquad (2.2)
\end{aligned}
$$

where
$$
\begin{aligned}
J_1 &= \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \tfrac{|a_m|^2}{m+n} \left(\tfrac{m}{n}\right)^{\frac{1}{2}} \left(1 - c(n) + c(m)\right) \\
J_2 &= \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \tfrac{|\bar{a}_n|^2}{m+n} \left(\tfrac{n}{m}\right)^{\frac{1}{2}} \left(1 - c(n) + c(m)\right)
\end{aligned}
$$

We can write the double series J_1 in the following form:

$$
J_1 = \sum_{n=1}^{\infty} \left(\sum_{m=1}^{\infty} \frac{1}{m+n} \left(\frac{n}{m}\right)^{\frac{1}{2}} \left(1 - c(m) + c(n)\right) \right) |a_n|^2.
$$

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Let $c\left(x\right)=\frac{\sqrt{x}}{1+\sqrt{x}}$. It is obvious that $1-\frac{\sqrt{x}}{1+\sqrt{x}}+\frac{\sqrt{n}}{1+\sqrt{n}}\geq 0$. It is known from Lemma 1.2 that the function $f\left(x\right)$ is monotonously decreasing. Hence we have

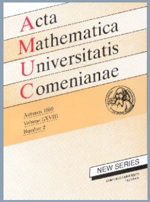
$$
\begin{aligned}
J_1 &= \sum_{n=1}^{\infty}\left(\sum_{m=1}^{\infty}\frac{1}{m+n}\left(\frac{n}{m}\right)^{\frac{1}{2}}\left(1-\frac{\sqrt{m}}{1+\sqrt{m}}+\frac{\sqrt{n}}{1+\sqrt{n}}\right)\right)\left|a_n\right|^2 \\
&\leq \sum_{n=1}^{\infty}\left\{\int_0^{\infty}\left(\frac{1}{x+n}\left(\frac{n}{x}\right)^{\frac{1}{2}}\right)\left(1-\left(\frac{\sqrt{x}}{1\;+\;\sqrt{x}}-\frac{\sqrt{n}}{1\;+\;\sqrt{n}}\right)\right)\mathrm{d}x\right\}\left|a_n\right|^2 \\
&= \pi\sum_{n=1}^{\infty}\left|a_n\right|^2-\pi\sum_{n=1}^{\infty}\omega\left(n\right)\left|a_n\right|^2
\end{aligned}
$$

where the weight function $\omega\left(n\right)$ is defined by (1.6).

Similarly,

$$
\begin{aligned}
J_2 &\leq \sum_{n=1}^{\infty}\left\{\int_0^{\infty}\frac{1}{x+n}\left(\frac{n}{x}\right)^{\frac{1}{2}}\left(1+\left(\frac{\sqrt{x}}{1\;+\;\sqrt{x}}-\frac{\sqrt{n}}{1\;+\;\sqrt{n}}\right)\right)\mathrm{d}x\right\}\left|\bar{a}_n\right|^2 \\
&= \pi\sum_{n=1}^{\infty}\left|a_n\right|^2+\pi\sum_{n=1}^{\infty}\omega\left(n\right)\left|a_n\right|^2.
\end{aligned}
$$

Whence $J_1J_2\leq\pi^2\left\{\left(\sum\limits_{n=1}^{\infty}\left|a_n\right|^2\right)^2-\left(\sum\limits_{n=1}^{\infty}\omega\left(n\right)\left|a_n\right|^2\right)^2\right\}.$



Consequently, we have

$$\left|\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{a_m\bar{a}_n}{m+n}\right|^2 \leq \pi^2\left\{\left(\sum_{n=1}^{\infty}|a_n|^2\right)^2-\left(\sum_{n=1}^{\infty}\omega(n)\,|a_n|^2\right)^2\right\} \tag{2.3}$$

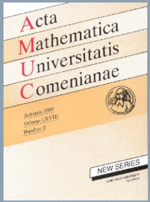
where the weight function $\omega(n)$ is defined by (1.6).

If $b_n \neq a_n$, then we can apply Schwarz's inequality to estimate the right-hand side of (2.1) as follows:

$$\begin{aligned}\left|\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{a_m\bar{b}_n}{m+n}\right|^4 &= \left\{\left|\int_0^1\left(\sum_{m=1}^{\infty}a_m t^{m-\frac{1}{2}}\right)\left(\sum_{n=1}^{\infty}\bar{b}_n t^{n-\frac{1}{2}}\right)\mathrm{d}t\right|^2\right\}^2\\ &\leq \left|\int_0^1\left(\sum_{m=1}^{\infty}|a_m|\,t^{m-\frac{1}{2}}\right)^2\mathrm{d}t\int_0^1\left(\sum_{n=1}^{\infty}|b_n|\,t^{n-\frac{1}{2}}\right)^2\mathrm{d}t\right|^2\\ &= \left|\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{a_m\bar{a}_n}{m+n}\right|^2\left|\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{b_m\bar{b}_n}{m+n}\right|^2 \qquad (2.4)\end{aligned}$$

And then by using the relation (2.3), from (2.4) and the inequality (2.1), we obtain at once. $\square$

Similarly, we can establish a new refinement of (1.2).



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Theorem 2.2. *Let $f(x)$ and $g(x)$ be two functions in complex number field. If $\int\limits_0^\infty |f(x)|^2\,\mathrm{d}x < +\infty$, $\int\limits_0^\infty |g(x)|^2\,\mathrm{d}x < +\infty$, then*

$$\left|\int_0^\infty\int_0^\infty \frac{f(x)\overline{g}(x)}{x+y}\mathrm{d}x\mathrm{d}y\right|^4 \le \pi^4\left\{\left(\int_0^\infty |f(x)|^2\,\mathrm{d}x\right)^2 - \left(\int_0^\infty \omega(x)\,|f(x)|^2\,\mathrm{d}x\right)^2\right\}$$
$$\times\left\{\left(\int_0^\infty |g(x)|^2\,\mathrm{d}x\right)^2 - \left(\int_0^\infty \omega(x)\,|g(x)|^2\,\mathrm{d}x\right)^2\right\} \tag{2.5}$$

where the weight function ω is defined by

$$\omega(x) = \begin{cases} 0 & x = 0 \\ \dfrac{\sqrt{x}}{x+1}\left(\dfrac{\sqrt{x}-1}{\sqrt{x}+1} - \dfrac{\ln x}{\pi}\right) & x > 0 \end{cases} \tag{2.6}$$

Its proof is similar to that of Theorem 2.1, it is omitted here.
For the convenience of the applications, we list the following result.

Corollary 2.3. *Let $f(x)$ be a function in complex number field. If $\int_0^\infty |f(x)|^2\,\mathrm{d}x < +\infty$, then*

$$\left|\int_0^\infty\int_0^\infty \frac{f(x)\overline{f}(y)}{x+y}\mathrm{d}x\mathrm{d}y\right|^2 \le \pi^2\left\{\left(\int_0^\infty |f(x)|^2\mathrm{d}x\right)^2 - \left(\int_0^\infty \omega(x)\,|f(x)|^2\,\mathrm{d}x\right)^2\right\} \tag{2.7}$$

where the weight function ω is defined by (2.6).

3. Applications

As applications, we shall give some new refinements of Hardy-Littlewood's theorem and Widder's theorem.

Let $f(x) \in L^2(0,1)$ and $f(x) \neq 0$ for all x. Define a sequence $\{a_n\}$ by $a_n = \int_0^1 x^n f(x)\mathrm{d}x$, $n = 0, 1, 2, \ldots$. Hardy-Littlewood ([1]) proved that

$$\sum_{n=0}^{\infty} a_n^2 < \pi \int_0^1 f^2(x)\mathrm{d}x, \tag{3.1}$$

where π is the best constant that the inequality (3.1) keeps valid.

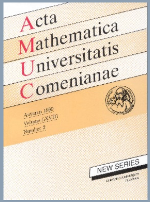
Theorem 3.1. *Let $f(x) \in L^2(0,1)$ and $f(x) \neq 0$ for all x. Define a sequence $\{a_n\}$ by $a_n = \int_0^1 x^{n-1/2} f(x)\mathrm{d}x \quad n = 1, 2, \ldots$. Then*

$$\left(\sum_{n=1}^{\infty} a_n^2\right)^2 \leq \pi \left\{ \left(\sum_{n=1}^{\infty} a_n^2\right)^2 - \left(\sum_{n=1}^{\infty} \omega(n)\, a_n^2\right)^2 \right\}^{\frac{1}{2}} \int_0^1 f^2(x)\,\mathrm{d}x \tag{3.2}$$

where $\omega(n)$ is defined by (1.6).

Proof. By our assumptions, we may write a_n^2 in the form

$$a_n^2 = \int_0^1 a_n x^{n-1/2} f(x)\mathrm{d}x.$$



Applying Cauchy-Schwarz's inequality we estimate the right hand side of (3.2) as follows

$$\left(\sum_{n=1}^{\infty} a_n^2\right)^2 = \left(\sum_{n=1}^{\infty} \int_0^1 a_n x^{n-1/2} f(x)\mathrm{d}x\right)^2 = \left\{\int_0^1 \left(\sum_{n=1}^{\infty} a_n x^{n-1/2}\right) f(x)\mathrm{d}x\right\}^2$$

$$\leq \int_0^1 \left(\sum_{n=1}^{\infty} a_n x^{n-1/2}\right)^2 \mathrm{d}x \int_0^1 f^2(x)\mathrm{d}x$$

$$= \int_0^1 \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} a_m a_n x^{m+n-1} \mathrm{d}x \int_0^1 f^2(x)\mathrm{d}x$$

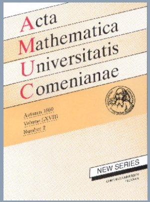
$$= \left(\sum_{m=}^{\infty} \sum_{n=1}^{\infty} \frac{a_m a_n}{m+n}\right) \int_0^1 f^2(x)\mathrm{d}x \tag{3.3}$$

It is known from (2.3) and (3.3) that the inequality (3.2) is valid. Therefore the theorem is proved. □

Let $a_n \geq 0$ $(n = 0, 1, 2, \ldots.)$, $A(x) = \sum\limits_{n=0}^{\infty} a_n x^n$, $A^*(x) = \sum\limits_{n=0}^{\infty} \frac{a_n x^n}{n!}$. Then

$$\int_0^1 A^2(x)\mathrm{d}x \leq \pi \int_0^{\infty} \left(\mathrm{e}^{-x} A^*(x)\right)^2 \mathrm{d}x \tag{3.4}$$

This is Widder's theorem (see [1]).



Theorem 3.2. *With the assumptions as the above-mentioned, it yields*

$$\left(\int_0^1 A^2(x)\,\mathrm{d}x\right)^2 \le \pi^2\left\{\left(\int_0^\infty \left(\mathrm{e}^{-x} A^*(x)\right)^2 \mathrm{d}x\right)^2 - \left(\int_0^\infty \omega(x)\left(\mathrm{e}^{-x} A^*(x)\right)^2 \mathrm{d}x\right)^2\right\} \tag{3.5}$$

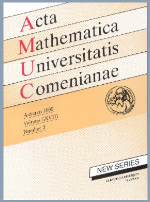
where $\omega(x)$ *is defined by* (2.6).

Proof. At first we have the following relation:

$$\begin{aligned}\int_0^\infty \mathrm{e}^{-t} A^*(tx)\mathrm{d}t &= \int_0^\infty \mathrm{e}^{-t}\sum_{n=0}^\infty \frac{a_n (xt)^n}{n!}\mathrm{d}t\\ &= \sum_{n=0}^\infty \frac{a_n x^n}{n!}\int_0^\infty t^n\,\mathrm{e}^{-t}\,\mathrm{d}t = \sum_{n=0}^\infty a_n x^n = A(x)\end{aligned}$$

Let $tx = s$. Then we have

$$\begin{aligned}\int_0^1 A^2(x)\mathrm{d}x &= \int_0^1\left\{\int_0^\infty \mathrm{e}^{-t} A^*(tx)\,\mathrm{d}t\right\}^2 \mathrm{d}x = \int_0^i\left(\int_0^\infty \mathrm{e}^{-\frac{s}{x}} A^*(s)\,\mathrm{d}s\right)^2 \frac{1}{x^2}\mathrm{d}x\\ &= \int_1^\infty\left(\int_0^\infty \mathrm{e}^{-sy} A^*(s)\mathrm{d}s\right)^2 \mathrm{d}y = \int_0^\infty\left(\int_0^\infty \mathrm{e}^{-s(u+1)} A^*(s)\,\mathrm{d}s\right)^2 \mathrm{d}u\\ &= \int_0^\infty\left(\int_0^\infty \mathrm{e}^{-su} f(s)\,\mathrm{d}s\right)^2 \mathrm{d}u = \int_0^\infty\int_0^\infty \frac{f(s)\,f(t)}{s\;+\;t}\mathrm{d}s\mathrm{d}t \qquad (3.6)\end{aligned}$$



where $f(x) = \mathrm{e}^{-x} A^*(x)$. By Corollary 2.3, the inequality (3.5) follows from (3.6) at once. $\square$

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