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Bisingular Integral In The Space Of Summable Functions

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ABSTRACT

It is obtained a Zigmund type estimate for the bisingular integral in the space of Summation functions. It is constructed an invariant functional space based on the inequality. Using the method of successive approximations it is proven the solvability of the nonlinear bisingular integral equation in invariant space.

KEYWORDS

Bisingular integral operator, Zigmund type estimate, invariant space, summable function.

INTRODUCTION

The classical boundedness theorem of singular operator with the Hilbert kernel in space L_(p) (p>1), it was proved by N.H. Luzin in [6] and M.Riesz in [16] for the cases p=2 and p>1, respectively.

Subsequently, this result was carried over in a number of papers for fairly wide classes of Jordan rectiable curves. A detailed prehistory of this issue is available in the work [9], also in the works of A.P. Calderon [11] ,[12], and [13].

To study the special integral

$$\tilde{u}(x) = \int_a^b \frac{u(s)}{s-x} ds \,, \qquad x \in (a,b)$$

(-∞<a<b<+∞) with the summable density in the work [4], [10] for a function u∈L_p^loc (a,b) , where L_p^loc (a,b) - is the set of functions, summable with the degree p in any compact segment of the interval (a,b). The characteristics were introduced

$$\Omega_p(u,\xi,\eta) = \left(\int_{a+\xi}^{b-\eta} |u(x)|^p dx \right)^{\frac{1}{p}} \quad \xi,\eta > 0\,, \xi+\eta \le b-a = l,$$

$$\omega_p(u,\delta,\xi,\eta) = \sup_{0<h\le\delta} \left(\int_{a+\xi}^{b-\eta-h} |u(x+h)-u(x)|^p dx \right)^{\frac{1}{p}} , \xi+\eta+h \le l, \delta > 0$$

and in the case 1<p<+∞ it is proved estimates, (Ω_p (u ̃),ω_p (u ̃)) , by (Ω_p (u), 〖ω〗_p (u)).

In the limiting case for p=∞ and u∈C_[a,b] these results were obtained in [3], [7], it was shown that estimates [2] in a certain sense are unimprovable. In [5] using M. Riesz's theorem about the bounded action of an operator u ̃ in the space L_p (a,b) the results are obtained in [1], [2].

One of the first papers, dedicated to the repeated special integral with the Hilbert kernel

$$(Bf)(x_1,x_2) = g(x_1,x_2) = \frac{1}{4\pi^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} f(x+t,y+\tau) ctg\frac{t}{2} ctg\frac{\tau}{2} dt d\tau$$

was a work of L. Cesari [14]. He proved that if $f \in H^2_{(\delta_1^\alpha,\delta_2^\alpha)}$, then

$$g \in H^2_{(\delta_1^\alpha |ln\delta_1|, \delta_2^\alpha |ln\delta_2|)}$$

Following L. Cesari, I.E. Zak [5] in his work also showed that the class of functions H_((δ_1^α,δ_2^α))^2 is not invariant with respect to the operator B. In the paper, it was proved that the classes of functions

$$H^{\alpha,\beta} = \left\{ f \in C_{[-\pi,\pi]^2} : \omega_f(\delta_1,\delta_2) = O\left(\delta_1^\alpha \delta_2^\beta\right), \omega_f^1(\delta_1) = O(\delta_1^\alpha), \omega_f^2(\delta_2) = O\left(\delta_2^\beta\right), 0 < \alpha,\beta < 1 \right\}.$$

are invariant with respect to the operator B.

RESULTS

Consider a bisingular integral of the form

$$\tilde{u}(x_1,x_2)=\int_{a_1}^{b_1}\int_{a_2}^{b_2}\frac{u(s_1,s_2)}{(s_1-x_1)(s_2-x_2)}ds_1ds_2\,,$$

where the function $u\in L_p^{loc}(\Delta)$, $\Delta=(a_1,b_1)\times(a_2,b_2)$ and $p>1$.

For the $u\in L_p^{loc}(\Delta)$ we introduce the characteristic

$$\Omega_p(u,\xi_1,\eta_1,\xi_2,\eta_2)=\left(\int_{a_1+\xi_1}^{b_1-\eta_1}\int_{a_2+\xi_2}^{b_2-\eta_2}|u(x_1,x_2)|^p\,dx_1dx_2\right)^{\frac{1}{p}}.$$

$$\overline{\omega}_p(u,\delta_1,\xi_1,\eta_1,\xi_2,\eta_2)$$
$$=\sup_{h_1\in E_1}\left(\int_{a_1+\xi_1}^{b_1-\eta_1-h_1}\int_{a_2+\xi_2}^{b_2-\eta_2}|u(x_1+h_1,x_2)-u(x_1,x_2)|^p\,dx_1dx_2\right)^{\frac{1}{p}}$$

$$\overline{\overline{\omega}}_p(u,\xi_1,\eta_1,\delta_2,\xi_2,\eta_2)$$
$$=\sup_{h_2\in E_2}\left(\int_{a_1+\xi_1}^{b_1-\eta_1}\int_{a_2+\xi_2}^{b_2-\eta_2-h_2}|u(x_1,x_2+h_2)-u(x_1,x_2)|^p\,dx_1dx_2\right)^{\frac{1}{p}}$$

$$\omega_p(u,\delta_1,\xi_1,\eta_1,\delta_2,\xi_2,\eta_2) = \sup_{h_1\in E_1 h_2\in E_2}\left(\int_{a_1+\xi_1}^{b_1-\eta_1-h_1}\int_{a_2+\xi_2}^{b_2-\eta_2-h_2}|\Delta u(x_1+h_1,x_1,x_2 + h_2,x_2)|^p\,dx_1dx_2\right)^{\frac{1}{p}}$$

where $0<\delta_i,\ \xi_i,\ \eta_i,\ \xi_i+\eta_i\le l_i=b_i-a_i$, $E_i=\{h_i: 0<h_i\le \min\{\delta_i, l_i-\xi_i-\eta_i\}$, $i=1,2$.

$$\Delta u(x_1+h_1,x_1,x_2+h_2,x_2) = u(x_1+h_1,x_2+h_2)-u(x_1+h_1,x_2)-u(x_1,x_2+h_2) + u(x_1,x_2).$$

Using [8], [15], it was proven

Teopema 1. Let $1<p<+\infty, \xi_i,\eta_i,\delta_i>0, \xi_i+\eta_i\le l_i, 0<\delta_i\le \min\{\xi_i,\eta_i\}$. Then from convergence of correspondence integrals it holds the following inequality

$$\omega_p(\tilde{u},\delta_1,\xi_1,\eta_1,\delta_2,\xi_2,\eta_2)\le$$

$$\le C_p[\frac{\delta_1\delta_2}{(\delta_1+\xi_1)(\delta_2+\xi_2)}\frac{1}{(\xi_1\xi_2)^{\frac{1}{q}}}\int_0^{\frac{\xi_1}{2}}\int_0^{\frac{\xi_2}{2}}\frac{\Omega_p\left(u,t_1,\frac{l_1}{2},t_2\frac{l_2}{2}\right)}{(t_1t_2)^{\frac{1}{p}}}dt_1dt_2+$$

$$+\frac{\delta_1\delta_2}{(\delta_1+\xi_1)(\delta_2+\eta_2)}\frac{1}{(\xi_1\eta_2)^{\frac{1}{q}}}\int_0^{\frac{\xi_1}{2}}\int_0^{\frac{\eta_2}{2}}\frac{\Omega_p\left(u,t_1\frac{l_1}{2},\frac{l_2}{2},t_2\right)}{(t_1t_2)^{\frac{1}{p}}}dt_1dt_2+$$

$$+\frac{\delta_1\delta_2}{(\delta_1+\eta_1)(\delta_2+\xi_2)}\frac{1}{(\eta_1\xi_2)^{\frac{1}{q}}}\int_0^{\frac{\eta_1}{2}}\int_0^{\frac{\xi_2}{2}}\frac{\Omega_p\left(u,\frac{l_1}{2},t_1,t_2,\frac{l_2}{2}\right)}{(t_1t_2)^{\frac{1}{p}}}dt_1dt_2+$$

$$+\frac{\delta_1\delta_2}{(\delta_1+\eta_1)(\delta_2+\eta_2)}\frac{1}{(\eta_1\eta_2)^{\frac{1}{q}}}\int_0^{\frac{\eta_1}{2}}\int_0^{\frac{\eta_2}{2}}\frac{\Omega_p\left(u,\frac{l_1}{2},t_1,\frac{l_2}{2},t_2\right)}{(t_1t_2)^{\frac{1}{p}}}dt_1dt_2+$$

$$+\frac{\delta_1}{(\delta_1+\xi_1)}\frac{1}{\xi_1^{\frac{1}{q}}}\int_0^{\frac{\xi_1}{2}}\frac{\overline{\omega}_p(u,t_1,\frac{l_1}{2},\delta_2,\frac{\xi_2}{2},\frac{\eta_2}{2})}{t_1^{\frac{1}{p}}}dt_1$$

$$+\frac{\delta_2}{(\delta_2+\xi_2)}\frac{1}{\xi_2^{\frac{1}{q}}}\int_0^{\frac{\xi_2}{2}}\frac{\overline{\overline{\omega}}_p(u,\delta_1,\frac{\xi_1}{2},\frac{\eta_1}{2},t_2\frac{l_2}{2})}{t_2^{\frac{1}{p}}}dt_2+$$

$$+\frac{\delta_1}{(\delta_1+\xi_1)}\frac{1}{\eta_1^{\frac{1}{q}}}\int_0^{\frac{\eta_1}{2}}\frac{\overline{\omega}_p(u,\frac{l_1}{2},t_1,\delta_2,\frac{\xi_2}{2},\frac{\eta_2}{2})}{t_1^{\frac{1}{p}}}dt_1+$$

$$+\frac{\delta_2}{(\delta_2+\xi_2)}\frac{1}{\eta_2^{\frac{1}{q}}}\int_0^{\frac{\eta_2}{2}}\frac{\overline{\overline{\omega}}_p(u,\delta_1,\frac{\xi_1}{2},\frac{\eta_1}{2},\frac{l_2}{2},t_2)}{t_2^{\frac{1}{p}}}dt_2+$$

$$+\omega_p\left(u,\delta_1,\frac{\xi_1}{2},\frac{\eta_1}{2},\delta_2,\frac{\xi_2}{2},\frac{\eta_2}{2}\right)$$

where the constant c_p is dependent on p.

Moreover, it is obtained estimates Ω_p (ῠ) ,ω ̅_p (ῠ) ,ω ̿_p (ῠ) . We denote by G the set of positive functions φ(ξ_1,η_1 〖,ξ〗 _2,η_2),(ψ) ̅(δ_1,ξ_1,η_1 〖,ξ〗 _2,η_2),ψ ̿(ξ_1,η_1 〖,δ_2,ξ〗 _2,η_2),ψ(δ_1,ξ_1,η_1 〖,δ_2,ξ〗 _2,η_2) defined for δ_i,ξ_(i ,) η_i>0,ξ_(i,)+η_i=l_i=b_i-a_i i=1,2, and such that the functions φ,ψ ̅,ψ ̿,ψ almost decreasing in ξ_1,ξ_2 (uniformly by other variables) , the functions ψ ̅,ψ ̿,ψ almost increasing in δ_1,δ_2 (uniformly by other variables), the functions

$$\frac{\bar{\psi}(\delta_1,\xi_1,\eta_1,\xi_2,\eta_2)}{\delta_1},\frac{\bar{\bar{\psi}}(\xi_1,\eta_1,\delta_2,\xi_2,\eta_2)}{\delta_2},\frac{\psi(\delta_1,\xi_1,\eta_1,\delta_2,\xi_2,\eta_2)}{\delta_1},\frac{\psi(\delta_1,\xi_1,\eta_1,\delta_2,\xi_2,\eta_2)}{\delta_2},$$

almost decreasing in δ_1, δ_2 (uniformly by other variables) , last but not less

$$\bar{\psi}(\delta_1,\xi_1,\eta_1,\xi_2,\eta_2),\bar{\bar{\psi}}(\xi_1,\eta_1,\delta_2,\xi_2,\eta_2),\psi(\delta_1,\xi_1,\eta_1,\delta_2,\xi_2,\eta_2)\to 0$$

for $\delta_1, \delta_2 \to 0$.

Let $\varphi, \bar{\psi}, \bar{\bar{\psi}}, \psi \in G$. Denote by $H^P_{\varphi,\bar{\psi},\bar{\bar{\psi}},\psi}$ the set of functions from $L_P^{loc}(\Delta)$ such that there exists constant $c_i > 0$ $(i = 1{,}4)$ and

$$\Omega_p(u,\xi_1,\eta_1,\xi_2,\eta_2) \le c_1\varphi(\xi_1,\eta_1,\xi_2,\eta_2),$$

$$\bar{\omega}_p(u,\delta_1,\xi_1,\eta_1,\xi_2,\eta_2) \le c_2\bar{\psi}(\delta_1,\xi_1,\eta_1,\xi_2,\eta_2),$$

$$\bar{\bar{\omega}}_p(u,\xi_1,\eta_1,\delta_2,\xi_2,\eta_2) \le c_3\bar{\bar{\psi}}(\xi_1,\eta_1,\delta_2,\xi_2,\eta_2),$$

$$\omega_p(u,\delta_1,\xi_1,\eta_1,\delta_2,\xi_2,\eta_2) \le c_4\psi(\delta_1,\xi_1,\eta_1,\delta_2,\xi_2,\eta_2).$$

The set $H^P_{\varphi,\bar{\psi},\bar{\bar{\psi}},\psi}$ by norm $\|u\|_{H^P_{\varphi,\bar{\psi},\bar{\bar{\psi}},\psi}} = \max\{c_1,c_2,c_3,c_4\}$ is a Banach space.

By G_0 we denote the set of function $\varphi, \bar{\psi}, \bar{\bar{\psi}}, \psi \in G$, such that the following integrals are convergent

$$\int_0^{\frac{l_1}{2}}\int_0^{\frac{l_2}{2}} \frac{\varphi\left(t_1,\frac{l_1}{2},t_2\frac{l_2}{2}\right)}{(t_1t_2)^{\frac{1}{p}}}dt_1dt_2,\quad \int_0^{\frac{l_1}{2}}\int_0^{\frac{l_2}{2}} \frac{\varphi\left(t_1\frac{l_1}{2},\frac{l_2}{2},t_2\right)}{(t_1t_2)^{\frac{1}{p}}}dt_1dt_2,$$

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$$\int_0^{\frac{l_1}{2}}\int_0^{\frac{l_2}{2}} \frac{\varphi\left(\frac{l_1}{2}, t_1, t_2, \frac{l_2}{2}\right)}{(t_1 t_2)^{\frac{1}{p}}} dt_1 dt_2, \quad \int_0^{\frac{l_1}{2}}\int_0^{\frac{l_2}{2}} \frac{\varphi\left(\frac{l_1}{2}, t_1, \frac{l_2}{2}, t_2\right)}{(t_1 t_2)^{\frac{1}{p}}} dt_1 dt_2,$$

$$\int_0^{\frac{l_1}{2}} \frac{\bar{\psi}(t_1, \frac{l_1}{2}, \delta_2, \frac{\xi_2}{2}, \frac{\eta_2}{2})}{t_1^{\frac{1}{p}}} dt_1, \quad \int_0^{\frac{l_2}{2}} \frac{\bar{\bar{\psi}}(\delta_1, \frac{\xi_1}{2}, \frac{\eta_1}{2}, t_2 \frac{l_2}{2})}{t_2^{\frac{1}{p}}} dt_2,$$

$$\int_0^{\frac{l_1}{2}} \frac{\bar{\psi}(\frac{l_1}{2}, t_1, \delta_2, \frac{\xi_2}{2}, \frac{\eta_2}{2})}{t_1^{\frac{1}{p}}} dt_1, \quad \int_0^{\frac{l_2}{2}} \frac{\bar{\bar{\psi}}(\delta_1, \frac{\xi_1}{2}, \frac{\eta_1}{2}, \frac{l_2}{2}, t_2)}{t_2^{\frac{1}{p}}} dt_2.$$

Now, we determine by H_P the set of positive functions $\varphi(\xi_1, \xi_2), \bar{\psi}(\xi_1, \delta_2, \xi_2)$, $\bar{\bar{\psi}}(\delta_1, \xi_1, \xi_2)$, $\psi(\delta_1, \xi_1, \delta_2, \xi_2,)$ satisfying the following conditions:

$$\int_0^{\frac{\xi_1}{2}}\int_0^{\frac{\xi_2}{2}} \frac{(t_1 t_2)^{\frac{1}{q}} \varphi(t_1, t_2)}{t_1 t_2} dt_1 dt_2 = 0((\xi_1 \xi_2)^{\frac{1}{q}} \varphi(\xi_1, \xi_2)),$$

$$\frac{\delta_1 \delta_2}{(\delta_1 + \xi_1)(\delta_2 + \xi_2)} \varphi(\xi_1, \xi_2) = 0\big(\psi(\delta_1, \xi_1, \delta_2, \xi_2,)\big),$$

$$\int_0^{\frac{\xi_1}{2}} \frac{t^{\frac{1}{q}} \bar{\psi}(t, \delta_2, \xi_2)}{t} dt = 0(\, \xi_1^{\frac{1}{q}} \bar{\psi}(\xi_1, \delta_2, \xi_2)),$$

$$\frac{\delta_1}{\delta_1 + \xi_1} \bar{\psi}(\xi_1, \delta_2, \xi_2) = 0\big(\psi(\delta_1, \xi_1, \delta_2, \xi_2,)\big),$$

$$\int_0^{\frac{\xi_2}{2}} \frac{t^{\frac{1}{q}}\bar{\bar{\psi}}(\delta_1,\xi_1,t)}{t}dt = 0(\,\xi_1{}^{\frac{1}{q}}\bar{\bar{\psi}}(\delta_1,\xi_1,\xi_2)),$$

$$\frac{\delta_2}{\delta_2+\xi_2}\bar{\bar{\psi}}(\delta_1,\xi_1,\xi_2) = 0\big(\psi(\delta_1,\xi_1,\delta_2,\xi_2,)\big),$$

$$\psi\left(\delta_1,\frac{\xi_1}{2},\delta_2,\frac{\xi_2}{2}\right) = 0\big(\psi(\delta_1,\xi_1,\delta_2,\xi_2,)\big),$$

$$\bar{\bar{\psi}}\left(\delta_1,\frac{\xi_1}{2},\xi_2\right) = 0\left(\bar{\bar{\psi}}(\delta_1,\xi_1,\xi_2)\right),$$

$$\bar{\psi}\left(\xi_1,\delta_2,\frac{\xi_2}{2}\right) = 0\left(\bar{\psi}(\xi_1,\delta_2,\xi_2)\right),$$

where the constants in expression "0" do not depend on $\delta_i,\xi_i\ (i=1,2)$.

In a view of definition we say that $(\varphi,\bar{\psi},\bar{\bar{\psi}},\psi) \in G_0H_P$, if $(\varphi,\bar{\psi},\bar{\bar{\psi}},\psi) \in G_0$

and

$$(\varphi\left(\xi_1,\tfrac{l_1}{2},\xi_2,\tfrac{l_2}{2}\right),\bar{\psi}\left(\delta_1,\xi_1,\tfrac{l_1}{2},\xi_2,\tfrac{l_2}{2}\right),\bar{\bar{\psi}}\left(\xi_1,\tfrac{l_1}{2},\delta_2,\xi_2,\tfrac{l_2}{2}\right),\psi\left(\delta_1,\xi_1,\tfrac{l_1}{2},\delta_2,\xi_2,\tfrac{l_2}{2}\right)),$$

$$(\varphi\left(\tfrac{l_1}{2},\eta_1,\xi_2,\tfrac{l_2}{2}\right),\bar{\psi}\left(\delta_1,\tfrac{l_1}{2},\eta_1,\xi_2,\tfrac{l_2}{2}\right),\bar{\bar{\psi}}\left(\tfrac{l_1}{2},\eta_1,\delta_2,\xi_2,\tfrac{l_2}{2}\right),\psi\left(\delta_1,\tfrac{l_1}{2},\eta_1,\delta_2,\xi_2,\tfrac{l_2}{2}\right)),$$

$$(\varphi\left(\xi_1,\tfrac{l_1}{2},\eta_2,\tfrac{l_2}{2}\right),\bar{\psi}\left(\delta_1,\xi_1,\tfrac{l_1}{2},\eta_2,\tfrac{l_2}{2},\right),\bar{\bar{\psi}}\left(\xi_1,\tfrac{l_1}{2},\delta_2,\eta_2,\tfrac{l_2}{2}\right),\psi\left(\delta_1,\xi_1,\tfrac{l_1}{2},\delta_2,\eta_2,\tfrac{l_2}{2}\right),$$

$$(\varphi\left(\tfrac{l_1}{2},\eta_1,\tfrac{l_2}{2}\eta_2\right),\bar{\psi}\left(\delta_1,\tfrac{l_1}{2},\eta_1,\tfrac{l_2}{2},\eta_2\right),\bar{\bar{\psi}}\left(\tfrac{l_2}{2},\eta_1,\tfrac{l_2}{2},\eta_2\right),\psi\left(\delta_1,\tfrac{l_2}{2},\eta_1,\tfrac{l_2}{2},\eta_2\right)) \in H_p$$

Теорема 2. If (φ,ψ ̅,ψ ̿,ψ)∈G_0 H_P. Then operator ū ̃ maps the space H_(φ,ψ ̅,ψ ̿,ψ)^Pitself and is bounded .

We note that the proof of this last Theorem 2 comes from the proof of Theorem 1 and by definition of the sets of G_0 H_P.

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CONCLUSION

Using the method of successive approximations it is proven the solvability of the nonlinear bisingular integral equation

$$u(x_1,x_2) = \lambda \int_0^{b_1}\int_0^{b_2} \frac{f(s_1,s_2,u(s_1,s_2))}{(s_1-x_1)(s_2-x_2)} ds_1 ds_2$$

in $H^P_{\varphi,\overline{\psi},\overline{\overline{\psi}},\psi}$, where the function $f(s_1,s_2,u)$ is defined on $(a_1,b_1)\times(a_2,b_2)\times(-\infty,+\infty)$ and λ- is a real parameter.

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