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Research Article

Bessel Transform of (k, γ)-Bessel Lipschitz Functions

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Using a generalized translation operator, we obtain an analog of Theorem 5.2 in Younis (1986) for the Bessel transform for functions satisfying the (k,γ)-Bessel Lipschitz condition in $L_{2,\alpha}(\mathbb{R}_+)$.

1. Introduction and Preliminaries

Younis Theorem 5.2 [1] characterized the set of functions in $L^2(\mathbb{R})$ satisfying the Cauchy Lipschitz condition by means of an asymptotic estimate growth of the norm of their Fourier transforms; namely, we have the following.

Theorem 1 (see [1]). *Let $f \in L^2(\mathbb{R})$. Then the followings are equivalent:*

(1) $\|f(x+h) - f(x)\|_2 = O(h^\alpha/(\log(1/h))^\beta)$ *as* $h \to 0$, $0 < \alpha < 1$, $\beta > 0$,

(2) $\int_{|x|\geq r} |\mathcal{F}(f)(x)|^2 dx = O(r^{-2\alpha}(\log r)^{-2\beta})$ *as* $r \to +\infty$,

where $\mathcal{F}$ stands for the Fourier transform of f.

In this paper, we obtain a generalization of Theorem 1 for the Bessel transform. For this purpose, we use a generalized translation operator.

Assume that $L_{2,\alpha}(\mathbb{R}_+)$; $\alpha > -1/2$ is the Hilbert space of measurable functions $f(t)$ on $\mathbb{R}_+$ with finite norm

$$\|f\|_{2,\alpha} = \left(\int_0^\infty |f(x)|^2 x^{2\alpha+1} dx\right)^{1/2}. \qquad (1)$$

Let

$$B = \frac{d^2}{dt^2} + \frac{(2\alpha+1)}{t}\frac{d}{dt} \qquad (2)$$

be the Bessel differential operator.

For $\alpha \geq -1/2$, we introduce the Bessel normalized function of the first kind j_α defined by

$$j_\alpha(z) = \Gamma(\alpha+1)\sum_{n=0}^{\infty}\frac{(-1)^n}{n!\Gamma(n+\alpha+1)}\left(\frac{z}{2}\right)^{2n}, \qquad (3)$$

where Γ is the gamma function (see [2]).

The function $y = j_\alpha(x)$ satisfies the differential equation

$$By + y = 0, \qquad (4)$$

with the initial conditions $y(0) = 1$ and $y'(0) = 0$. $j_\alpha(z)$ is function infinitely differentiable, even, and, moreover, entirely analytic.

Lemma 2. *For $x \in \mathbb{R}_+$ the following inequality is fulfilled:*

$$\left|1 - j_\alpha(x)\right| \geq c, \qquad (5)$$

with $x \geq 1$, where $c > 0$ is a certain constant which depends only on α.

Proof. Analog of Lemma 2.9 is in [3]. □

Lemma 3. *The following inequalities are valid for Bessel function j_α:*

(1) $|j_\alpha(x)| \leq 1$, *for all* $x \in \mathbb{R}^+$,

(2) $1 - j_\alpha(x) = O(x^2)$, $0 \leq x \leq 1$.

Proof. See [4]. □

The Bessel transform we call the integral transform from [2, 5, 6]

$$\widehat{f}(\lambda)=\int_0^{\infty} f(t)\, j_\alpha(\lambda t)\, t^{2\alpha+1}dt, \quad \lambda\in\mathbb{R}^+. \quad (6)$$

The inverse Bessel transform is given by the formula

$$f(t)=\left(2^{\alpha}\Gamma(\alpha+1)\right)^{-2}\int_0^{\infty}\widehat{f}(\lambda)\, j_\alpha(\lambda t)\,\lambda^{2\alpha+1}d\lambda. \quad (7)$$

We have the Parseval's identity

$$\|\widehat{f}\|_{2,\alpha}=2^{\alpha}\Gamma(\alpha+1)\,\|f\|_{2,\alpha}. \quad (8)$$

In $L_{2,\alpha}(\mathbb{R}_+)$, consider the generalized translation operator T_h defined by

$$T_h f(t)=c_\alpha\int_0^{\pi} f\left(\sqrt{t^2+h^2-2th\cos\varphi}\right)\sin^{2\alpha}\varphi\, d\varphi, \quad (9)$$

where

$$c_\alpha=\left(\int_0^{\pi}\sin^{2\alpha}\varphi\, d\varphi\right)^{-1}=\frac{\Gamma(\alpha+1)}{\Gamma(1/2)\,\Gamma(\alpha+(1/2))}. \quad (10)$$

The following relations connect the generalized translation operator and the Bessel transform; in [7] we have

$$\left(\widehat{\mathrm{T}_h f}\right)(\lambda)=j_\alpha(\lambda h)\,\widehat{f}(\lambda). \quad (11)$$

2. Main Result

In this section we give the main result of this paper. We need first to define (k,γ)-Bessel Lipschitz class.

Definition 4. Let $0<k<1$ and $\gamma\geq 0$. A function $f\in L_{2,\alpha}(\mathbb{R}^+)$ is said to be in the (k,γ)-Bessel Lipschitz class, denoted by $\mathrm{Lip}(k,\gamma,2)$, if

$$\|T_h f(t)-f(t)\|_{2,\alpha}=O\left(\frac{h^k}{(\log(1/h))^{\gamma}}\right), \quad \text{as } h\longrightarrow 0. \quad (12)$$

Our main result is as follows.

Theorem 5. *Let $f\in L_{2,\alpha}(\mathbb{R}^+)$. Then the followings are equivalents*

(1) $f\in\mathrm{Lip}(k,\gamma,2)$.

(2) $\int_r^{\infty}|\widehat{f}(\lambda)|^2\lambda^{2\alpha+1}d\lambda = O(r^{-2k}/(\log r)^{2\gamma})$, *as* $r\to+\infty$.

Proof. (1) ⇒ (2) Assume that $f\in\mathrm{Lip}(k,\gamma,2)$. Then we have

$$\|\mathrm{T}_h f(t)-f(t)\|_{2,\alpha}^2=\frac{1}{(2^{\alpha}\Gamma(\alpha+1))^2}\int_0^{\infty}|1-j_\alpha(\lambda h)|^2\left|\widehat{f}(\lambda)\right|^2\lambda^{2\alpha+1}d\lambda. \quad (13)$$

If $\lambda\in[1/h,2/h]$ then $\lambda h\geq 1$ and Lemma 2 implies that

$$1\leq\frac{1}{c^2}\left|1-j_\alpha(\lambda h)\right|. \quad (14)$$

Then

$$\begin{aligned}\int_{1/h}^{2/h}\left|\widehat{f}(\lambda)\right|^2\lambda^{2\alpha+1}d\lambda &\leq\frac{1}{c^2}\int_{1/h}^{2/h}|1-j_\alpha(\lambda h)|^2\left|\widehat{f}(\lambda)\right|^2\lambda^{2\alpha+1}d\lambda\\ &\leq\frac{1}{c^2}\int_0^{\infty}|1-j_\alpha(\lambda h)|^2\left|\widehat{f}(\lambda)\right|^2\lambda^{2\alpha+1}d\lambda\\ &=O\left(\frac{h^{2k}}{(\log(1/h))^{2\gamma}}\right).\end{aligned} \quad (15)$$

We obtain

$$\int_r^{2r}\left|\widehat{f}(\lambda)\right|^2\lambda^{2\alpha+1}d\lambda\leq C\frac{r^{-2k}}{(\log r)^{2\gamma}}, \quad (16)$$

where C is a positive constant.

So that

$$\begin{aligned}\int_r^{\infty}\left|\widehat{f}(\lambda)\right|^2\lambda^{2\alpha+1}d\lambda &=\left[\int_r^{2r}+\int_{2r}^{4r}+\int_{4r}^{8r}+\cdots\right]\left|\widehat{f}(\lambda)\right|^2\lambda^{2\alpha+1}d\lambda\\ &\leq C\frac{r^{-2k}}{(\log r)^{2\gamma}}+C\frac{(2r)^{-2k}}{(\log 2r)^{2\gamma}}+C\frac{(4r)^{-2k}}{(\log 4r)^{2\gamma}}+\cdots\\ &\leq C\frac{r^{-2k}}{(\log r)^{2\gamma}}\left(1+2^{-2k}+\left(2^{-2k}\right)^2+\left(2^{-2k}\right)^3+\cdots\right)\\ &\leq CK\frac{r^{-2k}}{(\log r)^{2\gamma}},\end{aligned} \quad (17)$$

where $K=(1-2^{-2k})^{-1}$ since $2^{-2k}<1$.

This proves that

$$\int_r^{\infty}\left|\widehat{f}(\lambda)\right|^2\lambda^{2\alpha+1}d\lambda=O\left(\frac{r^{-2k}}{(\log r)^{2\gamma}}\right) \quad \text{as } r\longrightarrow+\infty. \quad (18)$$

(2) ⇒ (1) Suppose now that

$$\int_r^{\infty}\left|\widehat{f}(\lambda)\right|^2\lambda^{2\alpha+1}d\lambda=O\left(\frac{r^{-2k}}{(\log r)^{2\gamma}}\right) \quad \text{as } r\longrightarrow+\infty. \quad (19)$$

We write

$$\int_0^{\infty}|1-j_\alpha(\lambda h)|^2\left|\widehat{f}(\lambda)\right|^2\lambda^{2\alpha+1}d\lambda=I_1+I_2, \quad (20)$$

where

$$I_1 = \int_0^{1/h} \left|1 - j_\alpha(\lambda h)\right|^2 \left|\widehat{f}(\lambda)\right|^2 \lambda^{2\alpha+1} d\lambda,$$
$$I_2 = \int_{1/h}^{\infty} \left|1 - j_\alpha(\lambda h)\right|^2 \left|\widehat{f}(\lambda)\right|^2 \lambda^{2\alpha+1} d\lambda. \quad (21)$$

Estimate the summands I_1 and I_2 from above. It follows from the inequality $|j_\alpha(\lambda h)| \leq 1$ that

$$\begin{aligned} I_2 &= \int_{1/h}^{\infty} \left|1 - j_\alpha(\lambda h)\right|^2 \left|\widehat{f}(\lambda)\right|^2 \lambda^{2\alpha+1} d\lambda \\ &\leq 4 \int_{1/h}^{\infty} \left|\widehat{f}(\lambda)\right|^2 \lambda^{2\alpha+1} d\lambda = O\left(\frac{h^{2k}}{(\log(1/h))^{2\gamma}}\right). \end{aligned} \quad (22)$$

To estimate I_1, we use the inequality (2) of Lemma 3.
Set

$$\phi(x) = \int_x^{\infty} \left|\widehat{f}(\lambda)\right|^2 \lambda^{2\alpha+1} d\lambda. \quad (23)$$

Using integration by parts, we obtain

$$\begin{aligned} I_1 &\leq -C_1 h^2 \int_0^{1/h} s^2 \phi'(s)\, ds \\ &\leq -C_1 \phi\left(\frac{1}{h}\right) + 2C_1 h^2 \int_0^{1/h} s\phi(s)\, ds \\ &\leq C_2 h^2 \int_0^{1/h} s\phi(s)\, ds \\ &\leq C_2 h^2 \int_0^{1/h} s s^{-2k} (\log s)^{-2\gamma} ds \\ &\leq C_3 h^{2k} (\log(1/h))^{-2\gamma}, \end{aligned} \quad (24)$$

where C_1, C_2, and C_2 are positive constants and this ends the proof. □

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