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Abel-Tauber theorems for Hankel and Fourier transforms and a problem of Boas

AKIHIKO INOUE AND HIDEYUKI KIKUCHI

ABSTRACT. We prove Abel-Tauber theorems for Hankel and Fourier transforms. For example, let f be a locally integrable function on $[0, \infty)$ which is eventually decreasing to zero at infinity. Let $\rho = 3, 5, 7, \dots$ and ℓ be slowly varying at infinity. We characterize the asymptotic behavior $f(t) \sim \ell(t)t^{-\rho}$ as $t \rightarrow \infty$ in terms of the Fourier cosine transform of f . Similar results for sine and Hankel transforms are also obtained. As an application, we give an answer to a problem of R. P. Boas on Fourier series.

1. Introduction and results

As a prototype, we use Fourier cosine transforms to explain our problem. Let f be a locally integrable, eventually decreasing function on $[0, \infty)$ which tends to zero at infinity, and let F_c be its Fourier cosine transform. Let $\rho > 0$ and ℓ be slowly varying at infinity (see below). We are concerned with Abel-Tauber theorems which characterize the asymptotic behavior $f(t) \sim \ell(t)t^{-\rho}$ as $t \rightarrow \infty$ in terms of F_c . It turns out that the values $1, 3, 5, \dots$ of ρ are exceptional. For $\rho \neq 1, 3, 5, \dots$, one can obtain the desired Abel-Tauber theorems using regular variation — or Karamata theory. See Bingham-Goldie-Teugels [BGT, Ch. 4], where references to earlier work by Hardy and Rogosinski, Aljančić, Bojanić and Tomić, Vuilleumier, Zygmund and others are given. However the same theorems do not hold for $\rho = 1, 3, 5, \dots$. These exceptional values are related to the power series expansion of the kernel $\cos x$ (see Soni-Soni [SS]).

In [I1], one of the authors showed that one could use Π -variation — or de Haan theory in the terminology of [BGT] — to obtain the desired Abel-Tauber theorem

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for cosine transforms when $\rho = 1$. For theorems of the same type, we refer to [I1] (cosine series and integrals), [I2] (sine series and integrals), [I3] (Fourier-Stieltjes coefficients), and Bingham-Inoue [BI] (Hankel transforms).

In this paper, we consider the remaining exceptional values, e.g., $\rho = 3, 5, \dots$ for cosine transforms. In fact, as in [BI], we consider those for Hankel transforms from the beginning; the results for cosine and sine transforms follow as special cases. As an application, we give an answer to a problem of R. P. Boas on Fourier series.

We write R_0 for the class of slowly varying functions at infinity, that is, the class of positive measurable ℓ , defined on some neighbourhood of infinity, satisfying

$$\ell(\lambda x)/\ell(x) \rightarrow 1 \quad (x \rightarrow \infty) \quad \forall \lambda > 0.$$

For $\ell \in R_0$, the class Π_ℓ is the class of measurable f satisfying

$$\{f(\lambda x) - f(x)\}/\ell(x) \rightarrow c \log \lambda \quad (x \rightarrow \infty) \quad \forall \lambda > 0$$

for some constant c , called the ℓ -index of f . See [BGT] for background.

Let $\nu \geq -1/2$, $t^{\nu+\frac{1}{2}}h(t) \in L_{\text{loc}}^1[0, \infty)$, and h be ultimately decreasing to zero at infinity. We consider the *Hankel Transform*

$$H_\nu(x) := \int_0^{\infty-} h(t)(xt)^{1/2} J_\nu(xt) dt \quad (0 < x < \infty), \quad (1.1)$$

where $\int_0^{\infty-}$ denotes an improper integral $\lim_{M \rightarrow \infty} \int_0^M$ and J_ν is the Bessel function

$$J_\nu(x) = \sum_{j=0}^{\infty} c_{\nu,j} x^{\nu+2j} \quad (0 \leq x < \infty)$$

with

$$c_{\nu,j} := \frac{(-1)^j}{2^{\nu+2j} \cdot j! \cdot \Gamma(\nu + j + 1)} \quad (\nu \geq -1/2, j = 0, 1, \dots). \quad (1.2)$$

Since the improper integral on the right of (1.1) converges uniformly on each (a, ∞) with $a > 0$, H_ν is finite and continuous on $(0, \infty)$.

For $n \in \mathbb{N}$ and $x \in (0, \infty)$, we define $\bar{H}_{\nu,n}$ by

$$\bar{H}_{\nu,n}(x) := x^{\nu+\frac{1}{2}+2n} \left\{ H_\nu(1/x) - \sum_{j=0}^{n-1} c_{\nu,j} \int_0^\infty t^{\nu+\frac{1}{2}+2j} h(t) dt \cdot x^{-\nu-\frac{1}{2}-2j} \right\} \quad (1.3)$$

if $\int_0^\infty t^{\nu-\frac{3}{2}+2n} h(t) dt < \infty$.

Theorem 1. Let $\ell \in R_0$ and $n \in \mathbb{N}$. Let $\nu \geq -1/2$, $t^{\nu+1/2}h(t) \in L_{\text{loc}}^1[0, \infty)$, and h be ultimately decreasing to zero at infinity, with Hankel transform H_ν . Then

$$h(t) \sim t^{-\nu-\frac{3}{2}-2n}\ell(t) \quad (t \rightarrow \infty) \quad (1.4)$$

if and only if

$$\int_0^\infty t^{\nu-\frac{3}{2}+2n}h(t)dt < \infty \quad \text{and} \quad \bar{H}_{\nu,n} \in \Pi_\ell \quad \text{with } \ell\text{-index } c_{\nu,n}. \quad (1.5)$$

Note that Theorem 1 includes results for Fourier cosine and sine transforms, as

$$x^{1/2}J_{-1/2}(x) = \sqrt{\frac{2}{\pi}} \cos x, \quad x^{1/2}J_{1/2}(x) = \sqrt{\frac{2}{\pi}} \sin x.$$

For $x \in (0, \infty)$, we define \bar{H}_ν by

$$\bar{H}_\nu(x) := x^{\nu+1/2}H_\nu(1/x). \quad (1.6)$$

We will prove Theorem 1 by reducing the problem to the following known result (which corresponds to the case $n = 0$ of (1.4)):

Theorem A ([BI], extending [I1], [I2]). Let ν , h , H_ν and ℓ be as in Theorem 1. Then

$$h(t) \sim t^{-\nu-\frac{3}{2}}\ell(t) \quad (t \rightarrow \infty) \quad (1.7)$$

if and only if

$$\bar{H}_\nu \in \Pi_\ell \quad \text{with } \ell\text{-index } c_{\nu,0}. \quad (1.8)$$

The cosine case $\nu = -\frac{1}{2}$ of Theorem A is due to [I1], the sine case $\nu = \frac{1}{2}$ to [I2], and the general case $\nu \geq -\frac{1}{2}$ to Bingham-Inoue [BI].

The theorems above treat the boundary cases to the following known Abel-Tauber theorem for Hankel transforms:

Theorem B ([RS], [SS], extending [P], [B]). Let ν , h , H_ν and ℓ be as in Theorem 1.

(1) For $0 < \rho < \nu + \frac{3}{2}$,

$$h(t) \sim t^{-\rho}\ell(t) \quad (t \rightarrow \infty) \quad (1.9)$$

if and only if

$$H_\nu(x) \sim x^{\rho-1} \ell(1/x) \cdot 2^{\frac{1}{2}-\rho} \frac{\Gamma(\frac{3}{4} + \frac{\nu}{2} - \frac{\rho}{2})}{\Gamma(\frac{1}{4} + \frac{\nu}{2} + \frac{\rho}{2})} \quad (x \rightarrow 0+). \quad (1.10)$$

(2) Let $n \in \mathbb{N}$ and $\nu - \frac{1}{2} + 2n < \rho < \nu + \frac{3}{2} + 2n$. Then (1.9) holds if and only if $\int_0^\infty t^{\nu-\frac{3}{2}+2n} h(t) dt < \infty$ and

$$\begin{aligned} H_\nu(x) &= \sum_{j=0}^{n-1} c_{\nu,j} \int_0^\infty t^{\nu+\frac{1}{2}+2j} h(t) dt \cdot x^{\nu+\frac{1}{2}+2j} \\ &\sim x^{\rho-1} \ell(1/x) \cdot 2^{\frac{1}{2}-\rho} \frac{\Gamma(\frac{3}{4} + \frac{\nu}{2} - \frac{\rho}{2})}{\Gamma(\frac{1}{4} + \frac{\nu}{2} + \frac{\rho}{2})} \quad (x \rightarrow 0+). \end{aligned} \quad (1.11)$$

The part (1) of Theorem B is due to Pitman [P], Bingham [B], and Ridenhour-Soni [RS], while the part (2) to Soni-Soni [SS].

We focus on Fourier (cosine and sine) transforms. Let $f \in L^1_{\text{loc}}[0, \infty)$ and f be ultimately decreasing to zero at infinity. We write F_c for the *Fourier cosine transform* of f :

$$F_c(x) = \int_0^{\infty-} f(t) \cos(xt) dt \quad (0 < x < \infty). \quad (1.12)$$

Similarly, let $g(t)t \in L^1_{\text{loc}}[0, \infty)$, and g be ultimately decreasing to zero at infinity. We write G_s for the *Fourier sine transform* of g :

$$G_s(x) = \int_0^{\infty-} g(t) \sin(xt) dt \quad (0 < x < \infty). \quad (1.13)$$

Now, at least formally,

$$F_c^{(2j)}(0) = (-1)^j \int_0^\infty t^{2j} f(t) dt, \quad G_s^{(2j+1)}(0) = (-1)^j \int_0^\infty t^{2j+1} g(t) dt.$$

So for $n \in \mathbb{N}$ we define $\bar{F}_{c,n}$ by

$$\bar{F}_{c,n}(X) := x^{2n} \left\{ F_c(1/x) - \sum_{j=0}^{n-1} \frac{F_c^{(2j)}(0)}{(2j)!} x^{-2j} \right\} \quad (0 < x < \infty) \quad (1.14)$$

if $F_c \in C^{2n-2}([0, \infty))$. Similarly, for $n \in \mathbb{N}$, we define $\bar{G}_{s,n}$ by

$$\bar{G}_{s,n}(x) := x^{2n+1} \left\{ G_s(1/x) - \sum_{j=0}^{n-1} \frac{G_s^{(2j+1)}(0)}{(2j+1)!} x^{-2j-1} \right\} \quad (0 < x < \infty) \quad (1.15)$$

if $G_s \in C^{2n-1}([0, \infty))$. Here as usual, $C^m([0, \infty))$ is the class of functions which are of $C^m(I)$ -class for some open neighbourhood I of $[0, \infty)$.

Theorem 2. Let $\ell \in R_0$ and $n \in \mathbb{N}$. Let $f \in L^1_{\text{loc}}[0, \infty)$ and f be ultimately decreasing to zero at infinity, with Fourier cosine transform F_c . Then

$$f(t) \sim t^{-2n-1}\ell(t) \quad (t \rightarrow \infty) \quad (1.16)$$

if and only if

$$F_c \in C^{2n-2}([0, \infty)) \quad \text{and} \quad \bar{F}_{c,n} \in \Pi_\ell \quad \text{with } \ell\text{-index } \frac{(-1)^n}{(2n)!}. \quad (1.17)$$

Theorem 3. Let $\ell \in R_0$ and $n \in \mathbb{N}$. Let $g(t) \in L^1_{\text{loc}}[0, \infty)$ and g be ultimately decreasing to zero at infinity, with Fourier sine transform G_s . Then

$$g(t) \sim t^{-2n-2}\ell(t) \quad (t \rightarrow \infty) \quad (1.18)$$

if and only if

$$G_s \in C^{2n-1}([0, \infty)) \quad \text{and} \quad \bar{G}_{s,n} \in \Pi_\ell \quad \text{with } \ell\text{-index } \frac{(-1)^n}{(2n+1)!}. \quad (1.19)$$

Remark. In Theorem 2, $F_c \in C^{2n-2}([0, \infty))$ implies that the limit $F_c(0+)$ exists and that F_c , with $F_c(0) := F_c(0+)$, is in $C^{2n-2}([0, \infty))$; similarly for the meaning of $G_s \in C^{2n-1}([0, \infty))$ in Theorem 3.

We will prove Theorems 2 and 3 using Theorem 1.

We give an application of Theorem 3 to probability theory. Let X be a real random variable defined on a probability space (Ω, \mathcal{F}, P) . The *tail-sum* of X is the function T defined by

$$T(x) := P(X \leq -x) + P(X > x) \quad (0 \leq x < \infty).$$

Note that T is finite and decreases to zero at infinity. Now

$$\{1 - U(\xi)\} / \xi = \int_0^{\infty-} T(x) \sin(x\xi) dx \quad (0 < \xi < \infty),$$

where U is the real part of the characteristic function of X :

$$U(\xi) := E[\cos(\xi X)] \quad (\xi \in \mathbb{R})$$

(see [BGT, p. 336]). By Theorem 3, the asymptotic behavior

$$T(x) \sim x^{-2n-2} \ell(x) \quad (x \rightarrow \infty)$$

with $n \in \mathbb{N}$ and $\ell \in R_0$ is characterized in terms of U .

We can apply Theorems 1 and A to Question 7.19 of Boas [Bo]. For $f \in L^1[0, \pi]$, we define its *Fourier cosine coefficients* a_n by

$$a_n := \frac{2}{\pi} \int_0^\pi f(t) \cos(nt) dt \quad (n = 1, 2, \dots), \quad := \frac{1}{\pi} \int_0^\pi f(t) dt \quad (n = 0). \quad (1.20)$$

Similarly, for $g \in L^1[0, \pi]$, we define its *Fourier sine coefficients* b_n by

$$b_n := \frac{2}{\pi} \int_0^\pi g(t) \sin(nt) dt \quad (n = 1, 2, \dots). \quad (1.21)$$

Theorem 4. *Let $f \in L^1[0, \pi]$ with Fourier cosine coefficients (a_k) . We assume that $a_k \geq 0$ for all $k \geq 0$. Let $n \in \mathbb{N}$ and $\ell \in R_0$. Then*

$$\sum_{k=m}^{\infty} a_k \sim \frac{\ell(m)}{m^{2n}} \cdot \frac{1}{2n} \quad (m \rightarrow \infty) \quad (1.22)$$

if and only if

$$f \in C^{2n-2}([0, \pi]) \quad \text{and} \quad \bar{f}_n \in \Pi_\ell \quad \text{with } \ell\text{-index } \frac{(-1)^n}{(2n)!}, \quad (1.23)$$

where

$$\bar{f}_n(x) := x^{2n} \left\{ f(1/x) - \sum_{j=0}^{n-1} \frac{f^{(2j)}(0)}{(2j)!} x^{-2j} \right\} \quad (1/\pi \leq x < \infty). \quad (1.24)$$

Corollary. *In Theorem 4, we further assume that (a_k) is decreasing. Then (1.23) is equivalent to*

$$a_m \sim \frac{\ell(m)}{m^{2n+1}} \quad (m \rightarrow \infty). \quad (1.25)$$

Theorem 5. Let $g \in L^1[0, \pi]$ with Fourier sine coefficients (b_k) . We assume that $b_k \geq 0$ for all $k \geq 1$. Let $n \in \mathbb{N}$ and $\ell \in \mathbb{R}_0$. Then

$$\sum_{k=m}^{\infty} b_k \sim \frac{\ell(m)}{m^{2n+1}} \cdot \frac{1}{2n+1} \quad (m \rightarrow \infty) \quad (1.26)$$

if and only if

$$g \in C^{2n-1}([0, \pi]) \quad \text{and} \quad \bar{g}_n \in \Pi_\ell \quad \text{with } \ell\text{-index } \frac{(-1)^n}{(2n+1)!}, \quad (1.27)$$

where

$$\bar{g}_n(x) := x^{2n+1} \left\{ g(1/x) - \sum_{j=0}^{n-1} \frac{g^{(2j+1)}(0)}{(2j+1)!} x^{-2j-1} \right\} \quad (1/\pi \leq x < \infty). \quad (1.28)$$

Corollary. In Theorem 5, we further assume that (b_k) is decreasing. Then (1.27) is equivalent to

$$b_m \sim \frac{\ell(m)}{m^{2n+2}} \quad (m \rightarrow \infty). \quad (1.29)$$

Remark. We understand that $L^1[0, \pi]$ consists of equivalence classes with respect to the equivalence relation $f_1 \sim f_2 \Leftrightarrow f_1 = f_2$ a.e. So, e.g., in (1.23), $f \in C^{2n-2}([0, \pi])$ implies that there exists a function in $C^{2n-2}([0, \pi])$ which lies in the equivalence class of f and that we identify the function with f . In particular, if $\sum_{k=0}^{\infty} |a_k| < \infty$, then by [Z, Ch. III, Theorem 3.9] (Theorem of Lebesgue on Cesàro summability) $f \in C([0, \pi])$ and we may assume that $f(x) = \sum_{k=0}^{\infty} a_k \cos(kx)$ for $0 \leq x \leq \pi$. Similarly, if $\sum_{k=1}^{\infty} |b_k| < \infty$, then $g \in C([0, \pi])$ and we may assume that $g(x) = \sum_{k=1}^{\infty} b_k \sin(kx)$ for $0 \leq x \leq \pi$.

For (1.26) with $n = 0$, we have the following:

Theorem 6. Let g , (b_k) and ℓ be as in Theorem 5. We write $\bar{g}(x) := xg(1/x)$ for $x \geq 1/\pi$. Then

$$\sum_{k=m}^{\infty} b_k \sim \frac{\ell(m)}{m} \quad (m \rightarrow \infty) \quad (1.30)$$

if and only if

$$g \in C([0, \pi]) \quad \text{and} \quad \bar{g} \in \Pi_\ell \quad \text{with } \ell\text{-index } 1. \quad (1.31)$$

See also [I2, Theorem 1.2].

Theorems 4, 5 and 6 treat the boundary cases to the following known results due to Yong [Y]:

Theorem C ([Y]). *Let f , (a_k) and ℓ be as in Theorem 4. Let $n \in \mathbb{N}$ and $2n - 1 < \rho < 2n + 1$. Then*

$$\sum_{k=m}^{\infty} a_k \sim \frac{\ell(m)}{m^{\rho-1}} \cdot \frac{1}{\rho-1} \quad (m \rightarrow \infty) \quad (1.32)$$

if and only if $f \in C^{2n-2}([0, \pi])$ and

$$f(x) - \sum_{j=0}^{n-1} \frac{f^{(2j)}(0)}{(2j)!} x^{2j} \sim \frac{\pi}{2\Gamma(\rho) \cos(\rho\pi/2)} x^{\rho-1} \ell(1/x) \quad (x \rightarrow 0+). \quad (1.33)$$

Theorem D ([Y]). *Let g , (b_k) and ℓ be as in Theorem 5. Let $n \in \mathbb{N}$ and $2n < \rho < 2n + 2$. Then*

$$\sum_{k=m}^{\infty} b_k \sim \frac{\ell(m)}{m^{\rho-1}} \cdot \frac{1}{\rho-1} \quad (m \rightarrow \infty) \quad (1.34)$$

if and only if $g \in C^{2n-1}([0, \pi])$ and

$$g(x) - \sum_{j=0}^{n-1} \frac{g^{(2j+1)}(0)}{(2j+1)!} x^{2j+1} \sim \frac{\pi}{2\Gamma(\rho) \sin(\rho\pi/2)} x^{\rho-1} \ell(1/x) \quad (x \rightarrow 0+). \quad (1.35)$$

Theorems 4, 5 and 6, together with Theorems C and D, give an answer to [Bo, Question 7.19].

2. Proof of Theorem 1

We note that (1.4) implies

$$\int_0^{\infty} t^{\nu-\frac{3}{2}+2n} h(t) dt < \infty. \quad (2.1)$$

So, when proving the equivalence of (1.4) and (1.5), we may assume (2.1).

We define h_0, \dots, h_{n-1} by

$$\begin{aligned} h_0(t) &:= \int_t^{\infty} h(s) s^{\nu+\frac{1}{2}} ds & (0 \leq t < \infty), \\ h_j(t) &:= \int_t^{\infty} h_{j-1}(s) ds & (0 \leq t < \infty, j = 1, \dots, n-1). \end{aligned}$$

Since h is eventually non-negative, h_j are all eventually decreasing. By Fubini's theorem,

$$\begin{aligned} h_j(0) &= \int_0^\infty dt_j t_j \int_{t_j}^\infty dt_{j-1} t_{j-1} \cdots \int_{t_1}^\infty h(t_0) t_0^{\nu+\frac{1}{2}} dt_0 \\ &= \int_0^\infty dt_0 h(t_0) t_0^{\nu+\frac{1}{2}} \int_0^{t_0} dt_1 t_1 \cdots \int_0^{t_{i-1}} t_j dt_j \\ &= \frac{1}{2^j j!} \int_0^\infty h(t) t^{\nu+\frac{1}{2}+2j} dt. \end{aligned}$$

Since

$$\begin{aligned} x^{-\mu} J_\mu(x) &= O(1) \quad (x \rightarrow \infty), \\ \frac{d}{dx} \{x^{-\mu} J_\mu(x)\} &= -x^{-\mu} J_{\mu+1}(x), \\ x^{-\mu} J_\mu(x) &\rightarrow c_{\mu,0} \quad (x \rightarrow 0+) \end{aligned}$$

for any $\mu \geq -1/2$ (see Watson [W], pages 199 and 45), we obtain, by integration by parts,

$$\begin{aligned} H_\nu(x) &= x^{\nu+\frac{1}{2}} \int_0^{\infty-} h(t) t^{\nu+\frac{1}{2}} \{(tx)^{-\nu} J_\nu(tx)\} dt \\ &= x^{\nu+\frac{1}{2}} h_0(0) c_{\nu,0} - x^{\nu+\frac{1}{2}+2} \int_0^{\infty-} h_0(t) t \{(tx)^{-\nu-1} J_{\nu+1}(tx)\} dt = \cdots \\ &= \sum_{j=0}^{n-1} (-1)^j x^{\nu+\frac{1}{2}+2j} h_j(0) c_{\nu+j,0} \\ &\quad + (-1)^n x^{\nu+\frac{1}{2}+2n} \int_0^{\infty-} h_{n-1}(t) t \{(tx)^{-\nu-n} J_{\nu+n}(tx)\} dt \\ &= \sum_{j=0}^{n-1} (-1)^j x^{\nu+\frac{1}{2}+2j} h_j(0) c_{\nu+j,0} + (-1)^n x^n \int_0^{\infty-} g(t) (tx)^{1/2} J_{\nu+n}(tx) dt, \end{aligned}$$

where

$$g(t) := t^{-\nu+\frac{1}{2}-n} h_{n-1}(t) \quad (0 < t < \infty).$$

Since

$$(-1)^j h_j(0) c_{\nu+j,0} = c_{\nu,j} \int_0^\infty t^{\nu+\frac{1}{2}+2j} h(t) dt,$$

we have

$$\bar{H}_{\nu,n}(x) = (-1)^n x^{(\nu+n)+\frac{1}{2}} \int_0^{\infty-} g(t) (t/x)^{1/2} J_{\nu+n}(t/x) dt. \quad (2.2)$$

Now $t^{(\nu+n)+\frac{1}{2}}g(t) \in L_{\text{loc}}^1[0, \infty)$ and g is eventually decreasing to zero, whence by Theorem A (with ν replaced by $\nu + n$) (1.5) is equivalent to

$$g(t) \sim t^{-\nu-n-\frac{3}{2}}\ell(t) \cdot \frac{(-1)^n c_{\nu,n}}{c_{\nu+n,0}} = t^{-\nu-n-\frac{3}{2}}\ell(t) \cdot \frac{1}{2^n n!} \quad (t \rightarrow \infty)$$

or

$$h_{n-1}(t) \sim t^{-2}\ell(t) \cdot \frac{1}{2^n n!} \quad (t \rightarrow \infty). \quad (2.3)$$

Since h_j is eventually decreasing, $\log \{h_j(t)t\}$ is slowly increasing, whence by the Monotone Density Theorem (see [BGT, §1.7]) (2.3) is equivalent to

$$h_0(t) = \int_t^\infty s^{\nu+\frac{1}{2}}h(s)ds \sim t^{-2n}\ell(t) \cdot \frac{1}{2^n} \quad (t \rightarrow \infty). \quad (2.4)$$

By assumption, h is eventually decreasing, whence $\log \{h(t)t^{\nu+\frac{1}{2}}\}$ is slowly increasing. Again by the Monotone Density Theorem, (2.4) is equivalent to (1.4). This completes the proof. \square

3. Proofs of Theorems 2 and 3

Lemma 3.1. *Let $n \in \mathbb{N}$, and let $f \in L_{\text{loc}}^1[0, \infty)$, f be ultimately decreasing to zero at infinity, with Fourier cosine transform F_c . If $F_c \in C^{2n-2}([0, \infty))$ and*

$$F_c(x) - \sum_{j=0}^{n-1} \frac{F_c^{(2j)}(0)}{(2j)!} x^{2j} = O(x^{2n-2}) \quad (x \rightarrow 0+), \quad (3.1)$$

then $\int_0^\infty t^{2n-2}f(t)dt < \infty$. In particular,

$$F_c^{(2j)}(x) = (-1)^j \int_0^\infty t^{2j}f(t) \cos(xt)dt \quad (0 \leq x < \infty, j = 0, \dots, n-1).$$

Remark. For the meaning of $F_c \in C^{2n-2}([0, \infty))$, see the remark just after the corollary to Theorem 3.

Proof. We first show that we lose no generality by supposing that f is finite and decreasing on $[0, \infty)$.

Choose X so large that f is finite and decreasing on $[X, \infty)$. Set

$$\tilde{f}(t) := f(X) \quad (0 \leq t < X), \quad := f(t) \quad (X \leq t),$$

and let \tilde{F}_c be its Fourier cosine transform:

$$\tilde{F}_c(x) := \int_0^{\infty-} \tilde{f}(t) \cos(xt) dt \quad (0 < x < \infty).$$

Set $D(x) := F_c(x) - \tilde{F}_c(x)$. Then

$$D(x) = \int_0^X \{f(t) - f(X)\} \cos(xt) dt \quad (0 < x < \infty),$$

and so D can be extended to a function in $C^\infty([0, \infty))$. Moreover,

$$\begin{aligned} D(x) - \sum_{j=0}^{n-1} \frac{D^{(2j)}(0)}{(2j)!} x^{2j} &= \int_0^X \{f(t) - f(X)\} \left\{ \cos(tx) - \sum_{j=0}^{n-1} \frac{(-1)^j}{(2j)!} (xt)^{2j} \right\} dt \\ &= O(x^{2n}) \quad (x \rightarrow 0+). \end{aligned}$$

So for F_c to be in $C^{2n-2}([0, \infty))$ and satisfy (3.1) it is necessary and sufficient that \tilde{F}_c has the same properties. Thus we may replace f by \tilde{f} — that is, we may assume that f is finite and decreasing on $[0, \infty)$.

Since $F_c(x) \rightarrow F_c(0)$ as $x \rightarrow 0+$, we have $\int_0^\infty f(t) dt < \infty$ by [SS, Theorem 20] (with $k(t) = \cos t$). In particular,

$$F_c(x) = \int_0^\infty f(t) \cos(xt) dt \quad (0 \leq x < \infty). \quad (3.2)$$

If $n \geq 2$, then we proceed to the next step. We follow the idea of the proofs of Chan[C, Theorems 1–10]. By (3.1), $F_c(x) - F_c(0) = O(x^2)$ as $x \rightarrow 0+$ or, by (3.2),

$$\int_0^\infty f(t) \{1 - \cos(tx)\} dt = O(x^2) \quad (x \rightarrow 0+).$$

Since the integrand is non-negative,

$$\int_0^{1/x} f(t) \{1 - \cos(xt)\} dt = O(x^2) \quad (x \rightarrow 0+).$$

By [C, Lemma 3] (or directly), $1 - \cos(tx) \geq (tx)^2/4$ for $0 \leq tx \leq 1$, whence

$$x^2 \int_0^{1/x} t^2 f(t) dt = O(x^2) \quad (x \rightarrow 0+)$$

or

$$\int_0^{1/x} t^2 f(t) dt = O(1) \quad (x \rightarrow 0+).$$

Thus $\int_0^\infty t^2 f(t) dt < \infty$ and so

$$F_c^{(2)}(x) = (-1) \int_0^\infty t^2 f(t) \cos(xt) dt \quad (0 \leq x < \infty). \quad (3.3)$$

If $n \geq 3$, then we proceed to the next step. By (3.1),

$$F_c(x) - \left\{ F_c(0) + \frac{F_c^{(2)}(0)}{2!} x^2 \right\} = O(x^4) \quad (x \rightarrow 0+)$$

or, by (3.3),

$$\int_0^\infty f(t) \left[\cos(tx) - \left\{ 1 - \frac{(xt)^2}{2!} \right\} \right] dt = O(x^4) \quad (x \rightarrow 0+).$$

Since

$$\cos u - \left(1 - \frac{u^2}{2!} \right) \geq 0 \quad (0 \leq u < \infty), \quad \geq \frac{u^4}{2 \cdot 4!} \quad (0 \leq u \leq 1)$$

(see [C, Lemma 3]), we have, as $x \rightarrow 0+$,

$$\frac{x^4}{2 \cdot 4!} \int_0^{1/x} t^4 f(t) dt \leq \int_0^{1/x} f(t) \left[\cos(tx) - \left\{ 1 - \frac{(xt)^2}{2!} \right\} \right] dt = O(x^4),$$

whence $\int_0^\infty t^4 f(t) dt < \infty$. Therefore

$$F_c^{(4)}(x) = (-1)^2 \int_0^\infty t^4 f(t) \cos(xt) dt \quad (0 \leq x < \infty).$$

If $n \geq 4$, then in a similar way we obtain inductively

$$\int_0^\infty t^{2j} f(t) dt < \infty, \quad F_c^{(2j)}(x) = (-1)^j \int_0^\infty t^{2j} f(t) \cos(xt) dt \quad (0 \leq x < \infty)$$

for $j = 3, \dots, n-1$. This completes the proof. \square

Proof of Theorem 2. If (1.16) holds, then $\int_0^\infty t^{2n-2} f(t) dt < \infty$, and so $F_c \in C^{2n-2}([0, \infty))$ and

$$F_c^{(2j)}(0) = (-1)^j \int_0^\infty t^{2j} f(t) dt \quad (j = 0, \dots, n-1). \quad (3.4)$$

Therefore, by Theorem 1 with $\nu = -1/2$, (1.17) follows.

Conversely, if F_c satisfies (1.17), then by [BGT, Theorem 3.7.4] we obtain (3.1), whence, by Lemma 3.1, $\int_0^\infty t^{2n-2} f(t) dt < \infty$ as well as (3.4). Therefore, by Theorem 1 with $\nu = -1/2$, (1.16) follows. \square

Lemma 3.2. *Let $n \in \mathbb{N}$, and let $g(t) \in L^1_{\text{loc}}[0, \infty)$, g be ultimately decreasing to zero at infinity, with Fourier sine transform G_s . If $G_s \in C^{2n-1}([0, \infty))$ and*

$$G_s(x) - \sum_{j=0}^{n-1} \frac{G_s^{(2j+1)}(0)}{(2j+1)!} x^{2j+1} = O(x^{2n-1}) \quad (x \rightarrow 0+), \quad (3.5)$$

then $\int_0^\infty t^{2n-1} g(t) dt < \infty$. In particular,

$$G_s^{(2j+1)}(x) = (-1)^j \int_0^\infty t^{2j+1} g(t) \cos(xt) dt \quad (0 \leq x < \infty, j = 0, \dots, n-1).$$

The proof of Lemma 3.2 is quite similar to that of Lemma 3.1; we use [SS, Theorem 20] with $k(t) = \sin t$ as well as [C, Lemma 2] instead of [C, Lemma 3]. We omit the details.

The proof of Theorem 3 is also quite similar to that of Theorem 2; we use Theorem 1 with $\nu = 1/2$ as well as Lemma 3.2 instead of Lemma 3.1. The details are omitted.

4. Proofs of Theorems 4, 5 and 6

Lemma 4.1. *Let $n \in \mathbb{N}$, and let $g \in L^1[0, \pi]$ with Fourier sine coefficients (b_k) . We assume $b_k \geq 0$ for all $k \geq 1$. If $g \in C^{2n-1}([0, \pi])$ and*

$$g(x) - \sum_{j=0}^{n-1} \frac{g^{(2j+1)}(0)}{(2j+1)!} x^{2j+1} = O(x^{2n-1}) \quad (x \rightarrow 0+), \quad (4.1)$$

then $\sum_{k=1}^{\infty} k^{2n-1}b_k < \infty$. In particular,

$$g^{(2j+1)}(x) = (-1)^j \sum_{k=1}^{\infty} k^{2j+1}b_k \cos(kx) \quad (0 \leq x \leq \pi, \quad j = 0, 1, \dots, n-1).$$

Proof. Since g' is bounded on $[0, \pi]$, $g \in \text{Lip } 1$ (in the sense of [Bo, pp. 46–47]). By [Bo, Theorem 7.28], we have $\sum_{k=1}^{\infty} kb_k < \infty$. Therefore,

$$g(x) = \sum_{k=1}^{\infty} b_k \sin(kx), \quad g'(x) = \sum_{k=1}^{\infty} kb_k \cos(kx) \quad (0 \leq x \leq \pi). \quad (4.2)$$

If $n \geq 2$, then we proceed to the next step. As in the proof of Lemma 3.1, we follow the idea of the proofs of [C, Theorems 1–10]. By (4.1), $g(x) - xg^{(1)}(0) = O(x^3)$ as $x \rightarrow 0+$, or by (4.2),

$$\sum_{k=1}^{\infty} b_k \{kx - \sin(kx)\} = O(x^3) \quad (x \rightarrow 0+).$$

Since

$$u - \sin u \geq 0 \quad (0 \leq u < \infty), \quad u - \sin u \geq \frac{u^3}{2 \cdot 3!} \quad (0 \leq u \leq 1)$$

(see [C, Lemma 2]), we have

$$\frac{m^{-3}}{2 \cdot 3!} \sum_{k=1}^m k^3 b_k \leq \sum_{k=1}^m b_k \{(k/m) - \sin(k/m)\} = O(m^{-3}) \quad (m \rightarrow \infty),$$

whence $\sum_{k=1}^{\infty} k^3 b_k < \infty$ and

$$g^{(3)}(x) = (-1) \sum_{k=1}^{\infty} k^3 b_k \cos(kx) \quad (0 \leq x \leq \pi).$$

If $n \geq 3$, then in a similar way we can show inductively

$$\sum_{k=1}^{\infty} k^{2j+1}b_k < \infty, \quad g^{(2j+1)}(x) = (-1)^j \sum_{k=1}^{\infty} k^{2j+1}b_k \cos(kx) \quad (0 \leq x \leq \pi)$$

for $j = 2, \dots, n-1$. This completes the proof. \square

Proof of Theorem 5. By [BGT, Theorem 3.7.4], (1.27) implies (4.1), whence by Lemma 4.1,

$$\sum_{k=1}^{\infty} k^{2n-1}b_k < \infty. \quad (4.3)$$

On the other hand, by partial summation, (1.26) also implies (4.3). Therefore, when proving the equivalence of (1.26) and (1.27), we may assume (4.3), whence $g \in C^{2n-1}([0, \pi])$, and

$$g^{(2j+1)}(x) = (-1)^j \sum_{k=1}^{\infty} k^{2j+1} b_k \cos(kx) \quad (0 \leq x \leq \pi, \quad j = 0, \dots, n-1).$$

Following [SS, pp. 620–621], we define a function h by

$$h(t) := \begin{cases} \sum_{k=1}^{\infty} b_k & (t < 1), \\ \sum_{k=n+1}^{\infty} b_k & (n \leq t < n+1, \quad n = 1, 2, \dots). \end{cases} \quad (4.4)$$

Then

$$\begin{aligned} g(x) &= - \int_{[0, \infty)} \sin(xt) dh(t) = x \int_0^{\infty-} h(t) \cos(xt) dt \\ &= \sqrt{\frac{\pi}{2}} x H_{-1/2}(x) \quad (0 \leq x \leq \pi) \end{aligned} \quad (4.5)$$

(recall $H_{-1/2}$ from (1.1)). On the other hand, for $j = 0, 1, \dots, n-1$,

$$\begin{aligned} \int_0^{\infty} t^{2j} h(t) dt &= \frac{1}{2j+1} \sum_{n=0}^{\infty} \left(\sum_{k=n+1}^{\infty} b_k \right) \{(n+1)^{2j+1} - n^{2j+1}\} \\ &= \frac{1}{2j+1} \sum_{k=1}^{\infty} b_k \sum_{n=0}^{k-1} \{(n+1)^{2j+1} - n^{2j+1}\} \\ &= \frac{1}{2j+1} \sum_{k=1}^{\infty} k^{2j+1} b_k = \frac{(-1)^j}{2j+1} g^{(2j+1)}(0). \end{aligned} \quad (4.6)$$

In particular, $\int_0^{\infty} t^{2n-2} h(t) dt < \infty$. Recall $\bar{H}_{-1/2, n}$ from (1.3). By (4.5) and (4.6),

$$\bar{H}_{-1/2, n}(x) = \sqrt{\frac{2}{\pi}} x^{2n+1} \left\{ g(1/x) - \sum_{j=0}^{n-1} \frac{g^{(2j+1)}(0)}{(2j+1)!} x^{-2j-1} \right\}. \quad (4.7)$$

Now (1.26) is equivalent to

$$h(t) \sim \frac{\ell(t)}{t^{2n+1}} \cdot \frac{1}{2n+1} \quad (t \rightarrow \infty),$$

which by Theorem 1 is equivalent to

$$\bar{H}_{-1/2, n} \in \Pi_{\ell} \text{ with } \ell\text{-index } \frac{c_{-1/2, n}}{2n+1} = \sqrt{\frac{2}{\pi}} \frac{(-1)^n}{(2n+1)!} \quad (4.8)$$

or to (1.27) by (4.7). This completes the proof. \square

Proof of Theorem 6. By [BGT, Theorem 3.7.4], (1.31) implies $g(t)/t \in L^1[0, \pi]$.

Therefore, since

$$\sum_{k=1}^n \sin kx = \frac{\sin\{\frac{1}{2}x(n+1)\} \sin(\frac{1}{2}xn)}{\sin(\frac{1}{2}x)}$$

and $|\sin(\frac{1}{2}x)| \geq x/\pi$ for $(0 \leq x \leq \pi)$, we obtain

$$\begin{aligned} \sum_{k=1}^n b_k &= \left| \frac{2}{\pi} \int_0^\pi g(t) \sum_{k=1}^n \sin(kt) dt \right| \\ &= \left| \frac{2}{\pi} \int_0^\pi g(t) \frac{\sin\{\frac{1}{2}t(n+1)\} \sin(\frac{1}{2}tn)}{\sin(\frac{1}{2}t)} dt \right| \\ &\leq 2 \int_0^\pi \frac{|g(t)|}{t} dt < \infty. \end{aligned}$$

Thus

$$\sum_{k=1}^{\infty} b_k < \infty. \quad (4.9)$$

On the other hand, (1.30) also implies (4.9). So, when proving the equivalence of (1.30) and (1.31), we may assume (4.9), whence $g \in C([0, \pi])$ and

$$g(x) = \sum_{k=1}^{\infty} b_k \sin kx \quad (0 \leq x \leq \pi).$$

We define h by (4.4). Then (1.30) is equivalent to

$$h(t) \sim \frac{\ell(t)}{t} \quad (t \rightarrow \infty). \quad (4.10)$$

On the other hand, by (4.5) and Theorem A with $\nu = -1/2$, (4.10) is equivalent to (1.31). This completes the proof. \square

Lemma 4.2. Let $n \in \mathbb{N}$, and let $f \in L^1[0, \pi]$ with Fourier cosine coefficients (a_k) .

We assume $a_k \geq 0$ for all $k \geq 0$. If $f \in C^{2n-2}([0, \pi])$ and

$$f(x) - \sum_{j=0}^{n-1} \frac{f^{(2j)}(0)}{(2j)!} x^{2j} = O(x^{2n-2}) \quad (x \rightarrow 0+), \quad (4.11)$$

then $\sum_{k=0}^{\infty} k^{2n-2} a_k < \infty$. In particular,

$$f^{(2j)}(x) = (-1)^j \sum_{k=0}^{\infty} k^{2j} a_k \cos(kx) \quad (0 \leq x \leq \pi, \quad j = 0, 1, \dots, n-1).$$

Proof. Since $f(x)$ approaches $f(0)$ as $x \rightarrow 0+$, we have $\sum_{k=0}^{\infty} a_k < \infty$ by [Bo, Theorem 7.26]. The rest of the proof is similar to that of Lemma 4.1 (see also the proof of Lemma 3.1), whence we omit the details. \square

Proof of Theorem 4. By [BGT, Theorem 3.7.4], (1.23) implies (4.11), whence by Lemma 4.2

$$\sum_{k=0}^{\infty} k^{2n-2} a_k < \infty. \quad (4.12)$$

On the other hand, by partial summation, (1.22) also implies (4.12). Therefore, when proving the equivalence of (1.22) and (1.23), we may assume (4.12), whence $f \in C^{2n-2}([0, \pi])$ and

$$f^{(2j)}(x) = (-1)^j \sum_{k=0}^{\infty} k^{2j} a_k \cos(kx) \quad (0 \leq x \leq \pi, \quad j = 0, 1, \dots, n-1).$$

Following [SS, p. 623], we define a function h by

$$h(t) := \begin{cases} \sum_{k=0}^{\infty} a_k & (t < 0), \\ \sum_{k=n+1}^{\infty} a_k & (n \leq t < n+1, \quad n = 0, 1, \dots). \end{cases} \quad (4.13)$$

Then (1.22) is equivalent to

$$h(t) \sim \frac{\ell(t)}{t^{2n}} \cdot \frac{1}{2n} \quad (t \rightarrow \infty). \quad (4.14)$$

Recall $H_{1/2}$ from (1.1). Since

$$f(x) = - \int_{[0, \infty)} \cos(xt) dh(t) = f(0) - x \int_0^{\infty-} h(t) \sin(xt) dt$$

for $0 \leq x \leq \pi$, we obtain

$$f(0) - f(x) = \sqrt{\frac{\pi}{2}} x H_{1/2}(x) \quad (0 \leq x \leq \pi). \quad (4.15)$$

First we assume $n = 1$. Then, by Theorem A with $\nu = 1/2$, (4.14) holds if and only if

$$\bar{H}_{1/2}(x) \in \Pi_\ell \text{ with } \ell\text{-index } \frac{c_{1/2,0}}{2} = \frac{1}{2} \sqrt{\frac{2}{\pi}}$$

(recall $\bar{H}_{1/2}$ from (1.6)), which by (4.15) is equivalent to (1.23) with $n = 1$.

Next we assume $n \geq 2$. For $j = 0, 1, \dots, n-2$,

$$\int_0^\infty t^{2j+1} h(t) dt = \frac{1}{2j+2} \sum_{k=0}^\infty k^{2j+2} a_k = \frac{(-1)^{j+1}}{2j+2} f^{(2j+2)}(0). \quad (4.16)$$

In particular, $\int_0^\infty t^{2n-3} h(t) dt < \infty$. Recall $\bar{H}_{1/2, n-1}$ from (1.3). By (4.15) and (4.16),

$$\bar{H}_{1/2, n-1}(x) = -\sqrt{\frac{2}{\pi}} x^{2n} \left\{ f(1/x) - \sum_{j=0}^{n-1} \frac{f^{(2j)}(0)}{(2j)!} x^{-2j} \right\}. \quad (4.17)$$

By Theorem 1 with $\nu = 1/2$, (4.14) is equivalent to

$$\bar{H}_{1/2, n-1} \in \Pi_\ell \text{ with } \ell\text{-index } \frac{c_{1/2, n-1}}{2n} = \sqrt{\frac{2}{\pi}} \frac{(-1)^{n-1}}{(2n)!},$$

which by (4.17) is equivalent to (1.23). This completes the proof \square

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