

2009

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Communications in the Analytic Theory of Continued Fractions, 2009, n. 16, p. 1-11

<http://hdl.handle.net/10016/5984>

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ON CONVERGENCE AND DIVERGENCE OF FOURIER EXPANSIONS WITH RESPECT TO SOME GEGENBAUER-SOBOLEV TYPE INNER PRODUCT

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ABSTRACT. Let introduce the discrete Sobolev-type inner product

$$\langle f, g \rangle = \int_{-1}^1 f(x)g(x)d\mu(x) + M[f(1)g(1) + f(-1)g(-1)] \\ + N[f'(1)g'(1) + f'(-1)g'(-1)],$$

where

$$d\mu(x) = \frac{\Gamma(2\alpha + 2)}{2^{(2\alpha+1)}\Gamma^2(\alpha + 1)}(1 - x^2)^\alpha dx, \quad M, N \geq 0, \quad \alpha > -1.$$

In this paper we prove the failure of a.e. convergence of the Fourier expansion in terms of the orthonormal polynomials with respect to the above inner product. Necessary conditions for mean convergence are also discussed.

1. INTRODUCTION

Let us first introduce some notation. We shall say that $f \in L^p(d\mu)$ if f is measurable on $[-1, 1]$ and $\|f\|_{L^p(d\mu)} < \infty$, where

$$\|f\|_{L^p(d\mu)} = \begin{cases} \left(\int_{-1}^1 |f(x)|^p d\mu(x) \right)^{\frac{1}{p}} & \text{if } 1 \leq p < \infty, \\ \text{ess sup}_{-1 < x < 1} |f(x)| & \text{if } p = \infty. \end{cases}$$

Now let introduce the Sobolev-type spaces

$$S_p = \{f : \|f\|_{S_p}^p = \|f\|_{L^p(d\mu)}^p + M[|f(1)|^p + |f(-1)|^p] \\ + N[|f'(1)|^p + |f'(-1)|^p] < \infty\}, \quad 1 \leq p < \infty,$$

$$S_\infty = \{f : \|f\|_{S_\infty} = \|f\|_{L^\infty(d\mu)} < \infty\}, \quad p = \infty.$$

2000 *Mathematics Subject Classification.* 42C05, 42C10.

Key words and phrases. Gegenbauer-Sobolev type polynomials, Fourier expansions, Cesàro means, norm convergence.

If $f, g \in S_2$ we can introduce the discrete Sobolev-type inner product

$$(1) \quad \langle f, g \rangle = \int_{-1}^1 f(x)g(x)d\mu(x) + M[f(1)g(1) + f(-1)g(-1)] \\ + N[f'(1)g'(1) + f'(-1)g'(-1)]$$

where $M, N \geq 0$. We denote by $\{\hat{B}_n^{(\alpha)}\}_{n \geq 0}$ the orthonormal polynomials with respect to the inner product (1) (see [1], [2], [11]). They are called Gegenbauer-Sobolev type polynomials. For $M = N = 0$, we get the classical Gegenbauer orthonormal polynomials that we will denote $\{p_n^{(\alpha)}\}_{n \geq 0}$. It is well known that, up to the Gegenbauer orthonormal polynomials, the polynomials $\hat{B}_n^{(\alpha)}$ for $M > 0$, $N \geq 0$ decay at the rate of $n^{-\alpha-3/2}$ at the end points 1 and -1 .

For $f \in S_1$, the Fourier expansion in terms of Gegenbauer-Sobolev type polynomials is

$$(2) \quad \sum_{k=0}^{\infty} \hat{f}(k) \hat{B}_k^{(\alpha)}(x),$$

where

$$\hat{f}(k) = \langle f, \hat{B}_k^{(\alpha)} \rangle, \quad k = 0, 1, \dots$$

The Cesàro means of order δ of the expansion (2) is defined by (see [19, p. 76-77])

$$\sigma_n^\delta f(x) = \sum_{k=0}^n \frac{A_{n-k}^\delta}{A_n^\delta} \hat{f}(k) \hat{B}_k^{(\alpha)}(x),$$

where $A_k^\delta = \binom{k+\delta}{k}$.

For $M = N = 0$ and $\alpha = 0$, Pollard [15] shows that for each $p < 4/3$ there exists a function $f \in L^p(dx)$ such that its Fourier expansion (2) diverges a.e. on $[-1, 1]$. Later on, Meaney [9] extends the result to $p = 4/3$. Furthermore, he proved that this is a special case of a divergence result for Jacobi polynomials series. The failure of a.e. convergence of the expansions (2), for $M > 0$ and $N = 0$, has been discussed in [4].

The main goal of this contribution is to prove that, for $M \geq 0$, $N > 0$, and $p_0 = \frac{4\alpha+4}{2\alpha+3}$, there are functions $f \in L^{p_0}(d\mu)$ whose expansions in terms of the polynomials associated with the Sobolev inner product (1) are divergent almost everywhere on $[-1, 1]$.

The structure of the paper is as follows. In Section 2, the background about the asymptotic behaviour of Gegenbauer-Sobolev type orthogonal polynomials is

presented. In Section 3 we show that, for $M, N \geq 0$, $1 < p < p_0$ and $0 < \delta < \frac{2\alpha+2}{p} - \frac{2\alpha+3}{2}$, there exists a function $f \in L^p(d\mu)$ with almost everywhere divergent Cesàro means of order δ . Finally, in Section 4 necessary conditions for the norm convergence of the Fourier expansion (2) are given.

Notice that the study of the convergence of the Fourier expansion in terms of the polynomials with respect to the discrete Sobolev inner product

$$\langle f, g \rangle = \int_{-1}^1 f(x)g(x)d\mu(x) + \sum_{k=1}^K \sum_{i=0}^{N_k} M_{k,i} f^{(i)}(a_k) g^{(i)}(a_k), \quad M_{k,i} > 0,$$

has been discussed in ([5], [6], [7], [16]).

2. GEGENBAUER-SOBOLEV TYPE POLYNOMIALS

We summarize some properties of Gegenbauer-Sobolev type polynomials that we will need in the sequel (see [1], [2], [11]). Throughout the manuscript positive constants are denoted by c, c_1, \dots ; unless specified, their values may vary at every occurrence. The notation $u_n \cong v_n$ means that the sequence u_n/v_n converges to 1 and notation $u_n \sim v_n$ means $c_1 u_n \leq v_n \leq c_2 u_n$ for n large enough.

The representation of $\hat{B}_n^{(\alpha)}$ in terms of Gegenbauer orthonormal polynomials is

$$(3) \quad \hat{B}_n^{(\alpha)}(x) = A_n(1-x^2)^2 p_{n-4}^{(\alpha+4)}(x) + B_n(1-x^2) p_{n-2}^{(\alpha+2)}(x) + C_n p_n^{(\alpha)}(x)$$

where

i) If $M = 0, N > 0$, then

$$A_n \cong \frac{2^{\alpha+1}\Gamma(\alpha+1)}{\alpha+2} \sqrt{\frac{\alpha+1}{\Gamma(2\alpha+3)}}, \quad B_n \cong -2^{\alpha+1}\Gamma(\alpha+1) \sqrt{\frac{\alpha+1}{\Gamma(2\alpha+3)}}, \quad C_n \cong -A_n,$$

ii) If $M > 0, N > 0$, then

$$A_n \cong 2^{\alpha+1}\Gamma(\alpha+1) \sqrt{\frac{\alpha+1}{\Gamma(2\alpha+3)}}, \quad B_n \sim -n^{-2\alpha-2}, \quad C_n \sim -n^{-2\alpha-2}$$

iii) If $M > 0, N = 0$, then

$$A_n = 0, \quad B_n \cong -2^{\alpha+1}\Gamma(\alpha+1) \sqrt{\frac{\alpha+1}{\Gamma(2\alpha+3)}}, \quad C_n \sim n^{-2\alpha-2}.$$

The polynomials $\hat{B}_n^{(\alpha)}$ satisfy the estimate

$$(4) \quad |\hat{B}_n^{(\alpha)}(\cos\theta)| = \begin{cases} O(\theta^{-\alpha-1/2}) & \text{if } c/n < \theta \leq \pi/2 \\ O(n^{\alpha+1/2}) & \text{if } 0 \leq \theta \leq c/n. \end{cases}$$

The inner strong asymptotic behaviour of $\hat{B}_n^{(\alpha)}$, for $\theta \in [\epsilon, \pi - \epsilon]$ and $\epsilon > 0$, is given by

$$(5) \quad \hat{B}_n^{(\alpha)}(\cos\theta) = c \left(\sin\frac{\theta}{2} \cos\frac{\theta}{2} \right)^{-\alpha-1/2} \cos(k\theta + \gamma) + O(n^{-1}),$$

where $k = n + \alpha + 1/2$ and $\gamma = -(\alpha + 1/2)\pi/2$.

The formula of Mehler-Heine type for Gegenbauer orthonormal polynomials is (see [17, Theorem 8.1.1] and [17, (4.3.4)])

$$(6) \quad \lim_{n \rightarrow \infty} n^{-\alpha-1/2} p_n^{(\alpha)} \left(\cos\left(\frac{z}{n}\right) \right) = z^{-\alpha} J_\alpha(z),$$

where α is a real number and $J_\alpha(z)$ is the Bessel function. This formula holds uniformly for $|z| \leq R$, for R a given positive real number.

From (8) it can be shown that

$$(7) \quad \lim_{n \rightarrow \infty} n^{-\alpha-1/2} p_n^{(\alpha)} \left(\cos\left(\frac{z}{n+j}\right) \right) = z^{-\alpha} J_\alpha(z)$$

holds uniformly for $|z| \leq R$, $R > 0$ fixed, and $j \in N \cup \{0\}$.

Lemma 1. For $|z| \leq R$, $R > 0$ fixed, we get

$$(8) \quad \lim_{n \rightarrow \infty} n^{-\alpha-1/2} \hat{B}_n^{(\alpha)} \left(\cos\left(\frac{z}{n}\right) \right) = z^{-\alpha} (c_1 J_{\alpha+4}(z) - c_2 J_{\alpha+2}(z) - c_3 J_\alpha(z))$$

where

- i) If $M = 0$, $N > 0$, then $c_i > 0$, $i = 1, 2, 3$, $c_1 = c_3$
- ii) If $M > 0$, $N > 0$, then $c_1 > 0$ and $c_2 = c_3 = 0$
- iii) If $M > 0$, $N = 0$, then $c_2 > 0$ and $c_1 = c_3 = 0$

Proof. From (3) we have

$$\begin{aligned} n^{-\alpha-1/2} \hat{B}_n^{(\alpha)} \left(\cos\frac{z}{n} \right) &= A_n \sin^4\left(\frac{z}{n}\right) n^{-\alpha-1/2} p_{n-4}^{(\alpha+4)} \left(\cos\frac{z}{n} \right) \\ &\quad + B_n \sin^2\left(\frac{z}{n}\right) n^{-\alpha-1/2} p_{n-2}^{(\alpha+2)} \left(\cos\frac{z}{n} \right) \\ &\quad + C_n n^{-\alpha-1/2} p_n^{(\alpha)} \left(\cos\frac{z}{n} \right) \end{aligned}$$

where $j \in N \cup \{0\}$.

Finally, we take the limit $n \rightarrow \infty$ and use the fact that $\sin\frac{z}{n} \cong \frac{z}{n}$ and (7) to obtain

$$(8). \quad \square$$

Now we will estimate the S_p norms for Gegenbauer-Sobolev polynomials

$$(9) \quad \|\hat{B}_n^{(\alpha)}\|_{S_p}^p = \int_{-1}^1 |\hat{B}_n^{(\alpha)}(x)|^p d\mu(x) + M \left[|(\hat{B}_n^{(\alpha)})(1)|^p + |(\hat{B}_n^{(\alpha)})(-1)|^p \right] \\ + N \left[|(\hat{B}_n^{(\alpha)})'(1)|^p + |(\hat{B}_n^{(\alpha)})'(-1)|^p \right],$$

where $1 \leq p < \infty$. Hence, it is sufficient to estimate the $L^p(d\mu)$ norms for $\hat{B}_n^{(\alpha)}$.

For $M = N = 0$ the calculation of this norm appears in [17, p.391. Exercise 91]

(see also [8, (2.2)]).

Lemma 2. *Let $M \geq 0$ and $N \geq 0$. For $\alpha \geq -1/2$ and $1 \leq q < \infty$*

$$\int_0^1 (1-x)^\alpha |\hat{B}_n^{(\alpha)}(x)|^q dx \sim \begin{cases} c & \text{if } 2\alpha > q\alpha - 2 + q/2, \\ \log n & \text{if } 2\alpha = q\alpha - 2 + q/2, \\ n^{q\alpha + q/2 - 2\alpha - 2} & \text{if } 2\alpha < q\alpha - 2 + q/2. \end{cases}$$

Proof. In order to prove the lemma, we follow the same lines as in [17, Theorem 7.34]. From (4), for $q\alpha + q/2 - 2\alpha - 2 \neq 0$, we have

$$\int_0^1 (1-x)^\alpha |\hat{B}_n^{(\alpha)}(x)|^q dx \sim \int_0^{\pi/2} \theta^{2\alpha+1} |\hat{B}_n^{(\alpha)}(\cos\theta)|^q d\theta \\ = O(1) \int_0^{n^{-1}} \theta^{2\alpha+1} n^{q\alpha + q/2} d\theta + O(1) \int_{n^{-1}}^{\pi/2} \theta^{2\alpha+1} \theta^{-q\alpha - q/2} d\theta \\ = O(n^{q\alpha + q/2 - 2\alpha - 2}) + O(1),$$

and for $q\alpha + q/2 - 2\alpha - 2 = 0$ we have

$$\int_0^1 \theta^{2\alpha+1} |\hat{B}_n^{(\alpha)}(x)|^q dx = O(\log n).$$

Now we will prove the lower estimates for integrals involving Gegenbauer-Sobolev type polynomials when $M = 0$ and $N > 0$. The proof of the other cases can be done in a similar way. According to Lemma 1 we have

$$\int_0^{\pi/2} \theta^{2\alpha+1} |\hat{B}_n^{(\alpha)}(\cos\theta)|^q d\theta > \int_0^{n^{-1}} \theta^{2\alpha+1} |\hat{B}_n^{(\alpha)}(\cos\theta)|^q d\theta \\ \cong c \int_0^1 (z/n)^{2\alpha+1} n^{q\alpha + q/2} n^{-1} |z^{-\alpha} (c_1 J_{\alpha+4}(z) - c_2 J_{\alpha+2}(z) - c_1 J_\alpha(z))|^q dz \\ \sim n^{q\alpha + q/2 - 2\alpha - 2}.$$

Using a similar argument as above, for $2\alpha = q\alpha + q/2 - 2$, we have

$$\begin{aligned} \int_0^{\pi/2} \theta^{2\alpha+1} |\hat{B}_n^{(\alpha)}(\cos\theta)|^q dx &> c \int_0^{n^{-1/2}} \theta^{2\alpha+1} |\hat{B}_n^{(\alpha)}(\cos\theta)|^q dx \\ &\cong c \int_0^{n^{1/2}} z^{2\alpha+1} |z^{-\alpha} (c_1 J_{\alpha+4}(z) - c_2 J_{\alpha+2}(z) - c_1 J_{\alpha}(z))|^q dz \\ &\geq c n^{\alpha+1} \geq c \log n. \end{aligned}$$

Finally, from (5) we obtain

$$\int_0^{\pi/2} \theta^{2\alpha+1} |\hat{B}_n^{(\alpha)}(\cos\theta)|^q d\theta > \int_{\pi/4}^{\pi/2} \theta^{2\alpha+1} |\hat{B}_n^{(\alpha)}(\cos\theta)|^q d\theta \sim c.$$

The proof of Lemma 2 is complete. \square

By using this lemma and [11, Proposition 4], we have:

Corollary 1. *Let $M \geq 0$ and $N \geq 0$. For $\alpha \geq -1/2$ and $1 \leq q < \infty$*

$$\|\hat{B}_n^{(\alpha)}(x)\|_{S_q} \sim \begin{cases} c & \text{if } 2\alpha > q\alpha - 2 + q/2, \\ (\log n)^{1/q} & \text{if } 2\alpha = q\alpha - 2 + q/2, \\ n^{\alpha+1/2-(2\alpha+2)/q} & \text{if } 2\alpha < q\alpha - 2 + q/2. \end{cases}$$

3. DIVERGENCE ALMOST EVERYWHERE

If the expansions (2) converges on a set, say E , of positive measure in $[-1,1]$ then

$$|c_n(f) \hat{B}_n^{(\alpha)}(x)| \rightarrow 0 \quad \text{when } n \rightarrow \infty$$

for $x \in E$. From Egorov's Theorem it follows that there is a subset $E_1 \subset E$ of positive measure such that

$$|c_n(f) \hat{B}_n^{(\alpha)}(x)| \rightarrow 0, \quad \text{when } n \rightarrow \infty,$$

uniformly for $x \in E_1$. Hence, from (5), we have

$$|c_n(f) (\cos(k\theta + \gamma) + O(n^{-1}))| \rightarrow 0, \quad \text{for } n \rightarrow \infty,$$

uniformly for $\cos\theta \in E_1$. Using the Cantor-Lebesgue Theorem, as described in [10, Subsection 1.5](see also [19, p.316]), we obtain

$$(10) \quad |c_n(f)| \rightarrow 0, \quad \text{when } n \rightarrow \infty.$$

From Lemma 2, for $\alpha > -1/2$ and $1 \leq q < \infty$, we have

$$(11) \quad \|\hat{B}_n^{(\alpha)}\|_{L^q(d\mu)} = \left(\frac{\Gamma(2\alpha+2)}{2^{2\alpha}\Gamma^2(\alpha+1)} \int_0^1 |\hat{B}_n^{(\alpha)}(x)|^q (1-x)^\alpha dx \right)^{1/q} \\ \sim \begin{cases} (\log n)^{1/q_0} & \text{if } p = p_0, \\ n^{\alpha+1/2-2\alpha/q-2/q} & \text{if } p < p_0. \end{cases}$$

where p is the conjugate of q i.e. $1/p + 1/q = 1$.

Now we can prove our first result

Theorem 1. *There is an $f \in S_{p_0}$ whose Fourier expansion (2) diverges almost everywhere on $[-1, 1]$.*

Proof. Taking into account (1), the Fourier coefficients of the series (2) can be written as

$$(12) \quad c_n(f) = c'_n(f) + M \left[f(1)\hat{B}_n^{(\alpha)}(1) + f(-1)\hat{B}_n^{(\alpha)}(-1) \right] \\ + N \left[f'(1) \left(\hat{B}_n^{(\alpha)} \right)'(1) + f'(-1) \left(\hat{B}_n^{(\alpha)} \right)'(-1) \right],$$

where

$$c'_n(f) = \int_{-1}^1 f(x) \hat{B}_n^{(\alpha)}(x) d\mu(x).$$

The uniform boundedness principle and (11) yield the existence of functions $f \in S_{p_0}$, supported on $[0, 1]$, such that the linear functional $c'_n(f)$ satisfies

$$\frac{c'_n(f)}{(\log n)^{1/(2q_0)}} \rightarrow \infty, \quad \text{when } n \rightarrow \infty.$$

Hence, from (12) and [11, Proposition 4], we obtain

$$\frac{c_n(f)}{(\log n)^{1/(2q_0)}} \rightarrow \infty, \quad \text{when } n \rightarrow \infty.$$

Since this result contradicts (12) then for this f the Fourier-Sobolev series diverges almost everywhere on $[-1, 1]$. \square

Next we show that, for some values of δ , there are functions with a.e. divergent Cesàro means of order δ .

Theorem 2. *Let α, p , and δ be real numbers such that $\alpha > -1/2$,*

$$1 < p < \frac{4\alpha+4}{2\alpha+3} \quad \text{if } M > 0, N \geq 0,$$

$$1 \leq p < \frac{4\alpha + 4}{2\alpha + 3}, \quad \text{if } M = 0, N \geq 0,$$

$$0 \leq \delta < \frac{2\alpha + 2}{p} - \frac{2\beta + 3}{2},$$

then there exists $f \in S_p$ whose Cesàro means $\sigma_n^\delta f(x)$ is divergent almost everywhere on $[-1, 1]$.

Proof. Let $M, N \geq 0$. If the expansion (2) is Cesàro summable of order δ on a set, say E , of positive measure in $[-1, 1]$, then from [19, Theorem 3.1.22] (see also [10, Lemma 1.1]) it follows that

$$|c_n(f)\hat{B}_n^{(\alpha)}(x)| = O(n^\delta)$$

for $x \in E$. Again, from Egorov's Theorem it follows that there is a subset $E_1 \subset E$ of positive measure such that

$$|c_n(f)\hat{B}_n^{(\alpha)}(x)| = O(n^\delta)$$

uniformly for $x \in E_1$. Hence, from (5), we have

$$|n^{-\delta}c_n(f)(\cos(k\theta + \gamma) + O(n^{-1}))| \leq c.$$

uniformly for $x = \cos\theta \in E_1$. Using again the Cantor-Lebesgue Theorem we obtain

$$(13) \quad \left| \frac{c_n(f)}{n^\delta} \right| \leq c, \quad \forall n \geq 1.$$

Suppose that

$$0 \leq \delta < \frac{2\alpha + 2}{p} - \frac{2\beta + 3}{2}.$$

If q is the conjugate of p , then from the last inequality, we get

$$\delta < \alpha + \frac{1}{2} - \frac{2\beta}{q} - \frac{2}{q}.$$

Using the argument given in [10, Subsection 1.4], (11), and [11, Proposition 4], for the linear functional $c'_n(f) = \int_{-1}^1 f(x)\hat{B}_n^{(\alpha)}(x)d\mu(x)$, it follows that there is an $f \in S_p$, where

$$1 < p < p_0 \quad \text{if } M > 0, N \geq 0,$$

$$1 \leq p < p_0, \quad \text{if } M = 0, N \geq 0,$$

supported on $[0, 1]$, such that

$$\frac{c'_n(f)}{n^\delta} \rightarrow \infty, \quad \text{when } n \rightarrow \infty.$$

So, from (12) and [11, Proposition 4], we obtain

$$\frac{c_n(f)}{n^\delta} \rightarrow \infty, \text{ when } n \rightarrow \infty.$$

Taking into account (13), for this f the Cesàro means $\sigma_n^\delta f(x)$ diverges almost everywhere. \square

Remark 1. Using formulae in [3], relating the Riesz and Cesàro means of order $\delta \geq 0$, we conclude that Theorem 2 also holds for the Riesz means.

4. NECESSARY CONDITIONS FOR THE NORM CONVERGENCE

The problem of the norm convergence of partial sums of the Fourier expansions in terms of Gegenbauer polynomials has been discussed by many authors. See [12], [13], [14], and the references therein.

Let $S_n f$ be the n -th partial sum of the expansion (2)

$$S_n(f, x) = \sum_{k=0}^n \hat{f}(k) \hat{B}_k^{(\alpha)}(x).$$

Theorem 3. Let $\alpha > -1/2$ and $1 < p < \infty$. If there exists a constant $c > 0$ such that

$$(14) \quad \|S_n f\|_{S_p} \leq c \|f\|_{S_p}$$

for every $f \in S_p$ and $n \geq 0$, then $p \in (p_0, q_0)$.

Proof. For the proof, we apply the same argument as in [13] (see also [18]). Assume that (4.1) holds. Then

$$\|\langle f, \hat{B}_n^{(\alpha)} \rangle \hat{B}_n^{(\alpha)}(x)\|_{S_p} \leq 2c \|f\|_{S_p}.$$

Therefore

$$\|\hat{B}_n^{(\alpha)}(x)\|_{S_p} \|\hat{B}_n^{(\alpha)}(x)\|_{S_q} < \infty,$$

where p is the conjugate of q . From Corollary 1, it follows that the last inequality holds if and only if $p \in (p_0, q_0)$.

The proof of Theorem 4.1 is completed. \square

Acknowledgements. *The work of the second author (FM) has been supported by Dirección General de Investigación, Ministerio de Educación y Ciencia of Spain, under grant MTM2006-13000-C03-02 and Comunidad de Madrid- Universidad Carlos III de madrid, grant CCG07-UC3M/ESP-3339.*

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