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On Jackson's Theorem

Eman Samir Abed-Ali
Department of Mathematics
College of Education
Babylon University

Abstract

We prove that for a function $f \in W_p^1[-1,1]$, $0 < p < 1$ and n,r in N , we have

$$\left(\int_{-1}^{1} f(x)dx - \sum_{j=1}^{n} \omega_j f(x_j) \right) \le c(r) n^{-1} \int_0^{1/n} \frac{\omega_\varphi^{r-1}(f',u)_p}{u^2} du$$

where $-1 < x_1 < \ldots < x_n < 1$ the roots of Legendre polynomial, and $\omega_\varphi^m(g,\delta)_p$, is the Ditzian-Totik mth modulus of smoothness of g in L_p.

1.Introduction

Let L_p, $0 < p < \infty$ be the set of all functions, which are measurable on $[a,b]$, such that

$$\|f\|_{L_p[a,b]} := \left(\int_a^b |f(x)|^p dx \right)^{1/p} < \infty .$$

And let $W_p^r[a,b]$, be the space of functions that $f^{(r)} \in L_p[a,b]$ and $f^{(r-1)}$ is absolutely continuous in $[a,b]$.

We believe that for approximation in $L_p, p < 1$ the measure of smoothness $\omega_\varphi^r(f,\delta)_p$ introduced by Ditzian and Totik [1] is the appropriate tool. Recall that

$$\omega_\varphi^r(f,\delta,[a,b])_p = \sup_{0<h\le\delta} \left(\int_a^b \left| \Delta_{h\varphi(x)}^r (f,x,[a,b]) \right|^p dx \right)^{1/p},$$

where

$$\Delta^r_{h\varphi(x)}(f,x,[a,b]) := \begin{cases} \sum_{k=0}^{r} \binom{r}{k} (-1)^{r-k} f\left(x - \frac{rh}{2} + kh\right), & if \quad x \pm \frac{rh}{2} \in [a,b] \\ 0, & o.w. \end{cases}$$

For $[a,b] := [-1,1]$ for simplicity we write $\|\cdot\|_p = \|\cdot\|_{L_p[a,b]}$, and $\omega^r_\varphi(f,\delta)_p := \omega^r_\varphi(f,\delta,[a,b])_p$.

Recall that the rate of best nth degree polynomial approximation is given by

$$E_n(f)_p := \inf_{p_n \in \Pi_n} \|f - p_n\|_p$$

where Π_n denote the set of all algebraic polynomials of degree not exceeding n.

To prove our theorem we need the following direct result given by:

Theorem 1.1. For n,r in N and $f \in L_p[-1,1]$

$$E_n(f)_p \le c\omega^r_\varphi\left(f, n^{-1}\right)_p \tag{1}$$

where c is a constant depending on r and p (if p<1). For $1 \le p \le \infty$ (1) was proved by Ditzian and Totik [1] and for 0<p<1, it has been proved by DeVore, Leviatan and Yu [2].

Now, consider the Gaussian Quadrature process [3]

$$\int_{-1}^{1} f(x)dx \approx \sum_{j=1}^{n} \omega_j f(x_j) =: I_n(f) \tag{2}$$

based on the roots $-1 < x_1 < \ldots < x_n < 1$ of the nth Legendre polynomial. Since this exact polynomial of degree less than 2n, we get for the error

$$e_n(f) = \int_{-1}^{1} f(x)dx - I_n(f)$$

in (2) by the definition of the degree of best approximation we have

$$e_n(f) \le 2E_{2n-1}(f)_\infty \tag{3}$$

where

$$\|f\|_\infty := \sup_{x\in[-1,1]} |f(x)|$$

(note that $\omega_j \ge 0$ and $\sum_{j=1}^{n} \omega_j$). The crude method of estimating $e_n(f)$ consists of applying Jackson estimate on the right of (3) from (1) we get the sharp inequality

$$e_n(f) \le c\omega_\varphi^r\left(f, n^{-1}\right)_\infty \qquad (4)$$

which already takes in to account the possibly less smooth behavior of f at ± 1. However the supremum norm in (5) is still too rough, and the natural question is whether for smooth functions one can get upper bounds for $e_n(f)$ using certain $L_p, p<1$ quasi-norm.

R. A. DeVore and L. R. Scott [3] found such estimates, they proved

$$e_n(f) \le c(s)n^{-s}\int_{-1}^{1}\left|f^{(s)}(x)\right|\left(1-x^2\right)^{5/2}dx \qquad (5)$$

first for s=1 which obviously implies

$$e_n(f) \le cn^{-1}E_{2n-2}(f')_{\varphi,p} \qquad p \ge 1 \qquad (6)$$

where $E_n(f)_{\varphi,p}$ means the best weighted approximation with weight $\varphi(x)$ of f in L_p defined by

$$E_n(f)_{\varphi,p} := \inf_{p_n \in \Pi_n}\left\|\varphi(f-p_n)\right\|_p.$$

They then proceeded to estimate $E_n(f')_p, p \ge 1$, using higher derivatives of f which finally yielded (5) for any $s \ge 1$.

2. The main result

Using (6) we obtain the following theorem

Theorem 2.1. For $f \in W_p^1[-1,1], 0<p<1$ we have

$$e_n(f) \le c(r)n^{-1}\int_0^{1/n}\frac{\omega_\varphi^{r-1}(f',u)_p}{u^2}du \qquad (7)$$

Of course the convergence of the integral on the right implies that f is L_p equivalent of a locally absolutely continuous function. We use this equivalent representative of f in the quadrature formula (Otherwise, we don't have even $e_n(f)=o(1)$)

Proof. Let $p_n \in \Pi_n$ be the best approximating polynomial for f in $L_p[-1,1], p<1$. Then $f = p_n + \sum_{k=0}^{\infty}\left(p_{2^{k+1}n} - p_{2^k n}\right)$

in $L_p[-1,1]$ (i.e. the expression in the right is the L_p equivalent of f which we need). From (6) and Markov-Bernstein type inequality (see for example [4])

$$\begin{aligned} e_n(f) &\le cn^{-1}E_{2n-2}(f')_{q,\varphi} \qquad q\ge 1 \\ &\le cn^{-1}E_n(f')_{q,\varphi} \\ &\le cn^{-1}\|\varphi(f'-p'_n)\|_q \\ &\le cn^{-1}\sum_{k=0}^{\infty} 2^{k+1}n\left\|\varphi\left(p_{2^{k+1}n}-p_{2^k n}\right)\right\|_q . \end{aligned}$$

Then using the fact that any two quasi norms are equivalent on the space of algebraic polynomials of a fixed degree we have

$$e_n(f)\le c(p)\sum_{k=0}^{\infty} 2^{k+1}nE_{2^k n}(f)_p \qquad p<1.$$

In view of (1) we get

$$e_n(f)\le c(p)\sum_{k=0}^{\infty}2^k n\omega_\varphi^r\left(f,2^{-k}n^{-1}\right)_p .$$

Now since $f\in W_p^1[-1,1], 0<p<1$, so that

$$\begin{aligned} e_n(f) &\le c(p)n^{-1}\sum_{k=0}^{\infty}2^k n\omega_\varphi^r\left(f,2^{-k}n^{-1}\right)_p \\ &\le c(p)n^{-1}\int_0^{1/n}\frac{\omega_\varphi^{r-1}(f',u)_p}{u^2}\,du . \end{aligned}$$

Provided the last integral convergence

As a final remark, we mention that similar bounds holds for many other systems of nodes and in (7) the right hand side has the order

$$\left(\int_{-1}^{x_n}|f|^p+\int_{x_n}^{1}|f|^p\right)^{1/p},$$

for any f constructed from analytic functions, $|x\pm 1|^s$ and iterated logarithms of these, which means that (7) is the best possible estimate for such functions.

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