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ON APPROXIMATION OF INTEGRABLE FUNCTIONS BY MODIFIED BERNSTEIN POLYNOMIALS

Suresh Prasad Singh

Abstract. We introduce a class of positive linear operators defined for functions integrable on the simplex $\Delta = \{(x_1, x_2) : x_1 \geq 0, x_2 \geq 0, x_1 + x_2 \leq 1\}$ and study some approximations theorems on it.

1. Introduction. Recently Derriennic [2] gave some results on approximations of a function f integrable on [0,1] by the modified Bernstein polynomials of order n defined by

$$(B_n f)(x) = (n+1) \sum_{k=0}^{n} P_{nk}(x) \int_0^1 P_{nk}(t) f(t) dt, \tag{1.1}$$
$$P_{nk}(x) = \binom{n}{k} x^k (1-x)^{n-k}.$$

Denoting by $X = X(x_1, x2)$, a point in the simplex $\Delta = \{(x_1, x_2) : x_1 \geq 0, x_2 \geq 0, x_1 + x_2 \leq\}$ and writing $f(V)$ for $f(v_1, v_2)$, we define a new class of positive linear operators of order n by

$$(L_n f)(X) = \frac{(n+2)!}{n!} \sum_{k=0}^{n} \sum_{l=0}^{n-k} p_{nkl}(X) \iint_{\Delta} p_{nkl}(V) dv_1 dv_2, \tag{1.2}$$

where $p_{nkl}(X) = \binom{n}{k}\binom{n-k}{l} x_1^k x_2^l (1 - x_1 - x_2)^{n-k-l}$. In this paper we prove some results on approximation of a function f integrable on the simplex Δ by the polynomials (1.2).

2. Basic Propositions. PROPOSITION 1. *For $n \leq 1$, $(p, q = O, 1, 2 \dots)$, one obtains*

$$(L_n v_1^p v_2^q)(X) = \frac{(n-2)!}{(n+p+g+2)!} \sum_{r=0}^{p} \binom{p!}{r} x_1^r \left[\sum_{l=0}^{q} \binom{q}{l} \frac{q!}{l!} x_2^l \cdots \frac{n!}{(n-r-l)!} \right].$$

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In particular we get

$$(L_n l)(X) = 1,\ \ (L_n v_i)(X) = (l + nx_i)/(n+3)$$
$$(L_n v_i^2)(X) = (2 + 4nx_i + n(n-1)x_i^2)/(n+3)(n+4);\ \ (i = 1, 2). \tag{2.3}$$

Proof. From definition (1.2), we get

$$I = (L_n v_1^p v_2^q(X) = \frac{(n+2)!}{n!}\sum_{k=0}^{n}\sum_{l=0}^{n-k} p_{nkl}(X)\iint_\Delta p_{nkl}(V) v_1^p v_2^q dv_1 dv_2$$

$$\frac{(n+2)!}{n!}\sum_{k=0}^{n}\sum_{l=0}^{n-k} p_{nkl}(X)\frac{n!}{k!l!(n-k-l)!}\iint_\Delta v_1^{k+p} v_2^{l+q}(1 - v_1 - v_2)^{n-k-l} dv_1 dv_2$$

Now the transformation $v_1 = t_1 t_2$, $v_2 = t_1(1 - t_2)$, so that

$$dv_1, dv_2 = |\partial(v_1, v_2)/\partial(t_1, t_2)| dt_1 dt_2$$

reduces I to

$$\begin{aligned} I &= \frac{(n+2)!}{(n+p+q+2)!}\sum_{k=0}^{n}\sum_{l=0}^{n-k} p_{nkl}(X)\frac{n!}{k!(n-k-l)l!}\cdot \\ &\cdot \int_0^1\int_0^1 t_1^{k+l+p+q+1}(1-t_1)^{n-k-l} dt_1 t_2^{k+p}(1-t_2)^{k+q} dt_2, \\ &= \frac{(n+2)!}{(n+p+q+2)!}\sum_{k=0}^{n}\sum_{l=0}^{n-k} p_{nkl}(X)\frac{(k+p)!(l+q)!}{k!q!}, \\ &= ((n+2)!/(n+p+q+2)!)S \qquad \text{(say)} \end{aligned} \tag{2.4}$$

Now we use the expression

$$(\partial^{p+q}/\partial x_1^p \partial x_2^q) x_1^p x_2^q (x_1 + x_2 + y)^n \tag{2.5}$$

to evaluate (2.4) Clearly

$$\begin{aligned} &(\partial^{p+q}/\partial x_1^p \partial x_2^q)) x_1^p x_2^q (x_1 + x_2 + y)^n \\ &= \sum_{k=0}^{n}\binom{n}{k} x_1^k \frac{(k+p)!}{k!}\Big[\frac{\partial^q}{\partial x_2^q}\{x_2^q (x_2 + y)^{n-k}\}\Big] \\ &= \sum_{k=0}^{n}\binom{n}{k} x_1^k \frac{(k+p)!}{k!}\sum_{l=0}^{n-k}\binom{n-k}{l} x_2^l y^{n-k-l}\frac{(l+q)!}{l!}. \end{aligned} \tag{2.6}$$

Again differentiating (2.5) by Leibnitz theorem, we get

$$\begin{aligned} &(\partial^{p+q}/\partial x_1^p \partial x_2^q)) x_1^p x_2^q (x_1 + x_2 + y)^n \\ &= \sum_{r=0}^{p}\binom{p}{r}\frac{p!}{r!} x_1^r \frac{n!}{(n-r)!}\Big\{\frac{\partial^q}{\partial x_2^q} x_2^q (x_1 + x_2 + y)^{n-r}\Big\} \\ &= \sum_{r=0}^{p}\binom{p}{r}\frac{p!}{r!} x_1^r \frac{n!}{(n-r)!}\Big[\sum_{l=0}^{q}\binom{q}{l}\frac{q!}{l!} x_2^l \frac{(n-r)!}{(n-r-0)!}(x_1 + x_2 + y)^{n-r-l}\Big] \end{aligned} \tag{2.7}$$

Now putting $y = l - x_1 - x_2$ in the expressions (2.6) and (2.7) and thus putting the value of S in (2.4), we get the required result.

PROPOSITION 2. *For $n \geq 1$ and $i, j \in \{1, 2\}$ we have*

$$L_n(v_i - x_i)(X) = 1 - 3x_i/(n+3), \tag{2.8}$$

$$L_n(v_i - x_i)^2(X) = 2nx_i(1 - xi)/(n+3)(n+4) + O(n^{-2}), \tag{2.9}$$

$$L_n(v_i - x_i)(v_j - x_j)(X) = -2x_ix_jn/(n+3)(n+4) + O(n^{-2}), \;\; i \neq j \tag{2.10}$$

$$L_n(v_i - x_i)^2(v_j - x_j)(X) = O(n^{-2}), \;\; i \neq j \tag{2.11}$$

$$L_n(v_i - x_i)^4(X) = O(n^{-2}) \tag{2.12}$$

Proof. Applying (2.1), by easy calculations we get the results (2.8) to (2.12).

PROPOSITION 3. *For $n \geq 1$ and $X \in \Delta$, we have*

$$L_n\left(\sum_{i=1}^{2}(v_i - x_i)^2\right)(X) \leq \frac{\max(8, n+2)}{(n+3)(n+4)} = Cn \quad (say) \tag{2.1.3}$$

Proof. We get from (2.3) that

$$\begin{aligned} &L_n\left(\sum_{i=1}^{2}(v_i - v_i)^2\right)(X) \\ &= [(2n-8)\{x_1(1-x_1) + x_2(1-x_2)\} + 4(1 + x_1^2 + x_2^2)]/(n+3)(n+4), \\ &= T/(n+3)(n+4) \end{aligned} \tag{2.14}$$

The maximum of the expression T on the simplex Δ for $n \geq 6$ occurs at $(1/2, 1/2)$ and it is $(n+2)$. The maximum value of T for $1 \leq n < 6$ is 8.

3. Main Results. THEOREM 1. *If f is an integrable and bounded function on the simplex Δ which has continuous derivatives up to the second order at a point $X \in \Delta$, then*

$$\lim_{n\to\infty} n\{(L_nf)(X) - f(X)\} = \sum_{i=1}^{2}\{(1 - 3x_i)f_i' + x_i(1 - xi)f_i''\} - 2x_1x_2f''_{x_1x_2}. \tag{3.1}$$

Proof. Using Taylors's formula [3] for two variables, we write

$$\begin{aligned} f(V &= f(X) + \sum_{i=1}^{2}(v_i - x_i)f_i' + \\ &+ (1/2)\sum_{i,j=1}^{2}(v_i - x_i)(v_i - x_j)\{f_{ij}' + \alpha_{i,j}((v_i - x_i)(v_i - x_j), \;\; (v_j - x_j))\}, \end{aligned} \tag{3.2}$$

where $\alpha_{i,j}(0,0) = 0$; $\alpha_{i,j}$ are integrable and bounded functions on the simplex Δ. Consequently for each $\varepsilon > 0$, there exist positive numbers δ_1 and δ_j such that $|\alpha_i(v_i - x_i, v_j - x_j)| < \varepsilon$ when ever $|v_i - x_i| < \delta_i$, $|v_i - x_j| < \delta_j$, $1 \le i, j \le 2$. Because of the boundedness of $\alpha_{i,j}$ on Δ, it follows that there exists $M > 0$ such that $|\alpha_{i,j}(v_i - x_i, v_j - x_j)| < M$, $1 \le i, j \le 2$. Now for every $\delta_i > 0$, we define the function $\lambda_{\delta_l}(v_l)$ by

$$\begin{aligned} \lambda_{\delta_l}(v_l) &= 1, \text{ when } |v_l - x_l| \ge \delta_l \\ &= 0, \text{ when } |v_l - x_l| < \delta_l \end{aligned}$$

Thus for all $(v_i, v_i) \in \Delta$, the inequalities

$$|\alpha_{i,j}(v_i - x_i, v_j - x_j) \le \varepsilon + M\lambda_{\delta_i}(v_i) + M\lambda_{\delta_i}(v_i), \ (1 \le i, j \le 2) \tag{3.3}$$

hold. Now in view of (2.8) to (2.12), (3.2) and (3.3) we get

$$(L_n f)(X) = f(X) + \sum_{i=1}^{2} \{(1 - 3x_i)f_i' + x_i(1 - x_i)f_i''\} - 2x_1x_2 f''_{x_1x_2} + E_n(x_1, x_2),$$

where

$$\begin{aligned} E_n(x_1, x_2) = \frac{(n+2)!}{2n!} &\sum_{k=0}^{n} \sum_{l=0}^{n-k} p_{nkl}(X) \cdot \\ &\cdot \iint_\Delta p_{nkl}(V) \left\{ \sum_{1 \le i,j \le 2} (v_i - x_i)(v_i - x_j)\alpha_{i,j}(v_I - x_i, v_j - x_j) \right\} dv_1 dv_2. \end{aligned}$$

It remains to show that $|nE_n| \to 0$ as $n \to \infty$. Clearly

$$\begin{aligned} |nEn(x_1, x_2)| \le (n/2)L_n[&\varepsilon(v_1 - x_1)^2 + \varepsilon(v_2 - x_2)^2 + 2M(v_1 - x_1)^4 \delta_1^{-2} + \\ &+ 2M(v_2 - x_2)^4 \delta_2^{-2} + 2(v_1 - x_1)(v_2 - x_2)\{\varepsilon + (v_1 - x_1)^2 \delta_1^{-2} + \\ &+ (v_2 - x_2)^2 \delta_2^{-2}\}](X). \end{aligned}$$

Choosing $\delta_1 = \delta_2 = n^{-1/4}$ and taking the limit as $n \to \infty$, we get $|nEn(x_1, x_2)| \le 2\varepsilon$. Since ε is arbitrary, we have $|nEn| \to 0$ as $n \to \infty$.

THEOREM 2. *Let f be continuous in Δ and $\omega(f; 1/\sqrt{n})$ be its modulus of continuity. Then for $n \ge 1$:*

$$\sup_{X \in \Delta} |(L_n f)(X) - f(X)| \le (1 + nC_n) \cdot \omega(f; n^{-l/2}), \tag{3.4}$$

where C_n is given in (2.13).

Proof. We know that

$$(L_n f)(X) - f(X) = \frac{(n+2)!}{2n!} \sum_{k=0}^{n} \sum_{l=0}^{n-k} p_{nkl}(X) \iint_\Delta p_{nkl}(V)\{f(V) - f(X)\} dv_1 dv_1.$$

Using the inequality

$$\omega(f;\delta) = \sup|f(V) - f(X)|, \ \ \delta > 0, \ \ \sqrt{(v_1 - x_1)^2 + (v_2 - x_2)^2} \leq \delta$$

we get

$$|(L_n f)(X) - f(X)| \leq \omega(f;\delta)\left\{(L_n 1)(X) + \delta^{-2} L_n\left(\sum_{i=1}^{2}(v_i - x_i)^2\right)(X)\right\}.$$

Taking $\delta = n$ and using (2.13), we get the required result.

it Remark. The result (3.4) can be obtained directly from Proposition 3 and Theorem 1 due to Censor [1].

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Department of Mathematics
Garhwal University, Sprinagar
U.P., India, 246174.

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