

On Lagrange and Hermite interpolation based on the Laguerre abscissas

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Abstract. A two-sided uniform estimate of the Lebesgue function for Lagrange and Hermite interpolation based on the Laguerre abscissas is established and an improved rate of convergence for Lagrange and Hermite interpolation is given.

1. Introduction

Let

$$L_n^{(\alpha)}(x) = e^x x^{-\alpha} (e^{-x} x^{n+\alpha})^{(n)} / n!, \quad n = 1, 2, \dots$$

be the Laguerre polynomial of degree n for $\alpha > -1$, with the normalization

$$L_n^{(\alpha)}(0) = \binom{n+\alpha}{n}$$

and

$$(1.1) \quad (0 <) x_{1n}^{(\alpha)} < x_{2n}^{(\alpha)} < \dots < x_{nn}^{(\alpha)}$$

its zeros. We shall write x_k instead of $x_{kn}^{(\alpha)}$ if there is no misunderstanding.

FREUD [1] and NÉVAI [2–4] studied Lagrange interpolation based on nodes (1.1). BALÁZS [5] considered the Hermite interpolation of degree $n + \alpha$ with the nodes (1.1) and 0, if α is an integer and f is α -time differentiable on $[0, \infty)$:

$$(1.2) \quad Q_{n\alpha}(f, x) = \sum_{k=1}^n f(x_k) l_k(x) (x/x_k)^{\alpha+1} + \sum_{i=0}^{\alpha} f^{(i)}(0) r_i(x),$$

where

$$l_k(x) = L_n^{(\alpha)}(x) / (L_n^{(\alpha)}(x_k)(x - x_k)), \quad k = 1, \dots, n$$

and

$$r_i(x) = x^i L_n^{(\alpha)}(x) / \left(i! \binom{n+\alpha}{n} \right), \quad i = 0, 1, \dots, \alpha$$

with the properties

$$r_i^{(s)}(0) = \begin{cases} 1, & \text{if } s = i \\ 0, & \text{if } 0 \leq s < i \end{cases}$$

and

$$r_i(x_k) = 0, \quad \text{for } k = 1, \dots, n; \quad i = 1, \dots, \alpha.$$

If $\alpha = 0$, $Q_{n0}(f, x)$ is the Lagrange interpolation. BALÁZS established some estimates of degree of approximation for functions and their derivatives by (1.2).

In this paper we shall first establish a two-sided uniform estimate of the Lebesgue function

$$\Lambda_n^{(\alpha)}(x) := \sum_{k=1}^n |l_k(x)| (x/x_k)^{\alpha+1} + \sum_{i=0}^{\alpha} |r_i(x)|$$

for the interpolation (1.2). Second, we will give degrees of approximation of functions and their derivatives by (1.2) that improve results of [5].

Throughout the paper, $O(1)$ or c are always independent of n , x , f and $f^{(i)}$ but may depend on α . The sign “ $A_n(x) \sim B_n(x)$ ” means that there exist two constants $0 < c_1 < c_2$ independent of n, x such that

$$c_1 B_n(x) \leq A_n(x) \leq c_2 B_n(x).$$

2. Main Results

Now we state our main results.

Theorem 2.1. *The estimate*

$$(2.1) \quad \left(\Lambda_n^{(\alpha)}(x) - 1 \right) \sim \begin{cases} |L_n^{(\alpha)}(x)| (n^{\frac{1}{4}-\alpha/2} x^{\frac{1}{4}+\alpha/2} (|\log nx| + 1) + n^{-\alpha}), & x \geq x_1 \\ |L_n^{(\alpha)}(x)| (nx^{\alpha+1} + n^{-\alpha}x), & 0 \leq x < x_1 \end{cases}$$

holds uniformly for $0 \leq x \leq \Delta$, where Δ is an arbitrary but fixed positive number.

Corollary 2.2. *The following estimate is valid:*

$$(2.2) \quad \left\| \Lambda_n^{(\alpha)}(x) \right\|_{[0, \Delta]} = O(\log n).$$

Theorem 2.3. *Let $f \in C^r[0, \infty)$ ($r \geq \alpha$, $r = 0, 1, \dots$). Then we have for $0 \leq x \leq \Delta$*

$$(2.3) \quad |f(x) - Q_{n\alpha}(f, x)| = O(1)\omega(f^{(r)}, n^{-\frac{1}{2}})(x^{\frac{1}{2}r} + x^{\frac{1}{2}\alpha+3/4})n^{-\frac{1}{2}r} \log n,$$

where $\omega(f^{(r)}, \cdot)$ is the modulus of continuity of $f^{(r)}$ on $[0, x_n]$.

Corollary 2.4. *If f satisfies the condition*

$$\omega(f, n^{-\frac{1}{2}}) \log n \rightarrow 0 \quad (n \rightarrow \infty),$$

on $[0, x_n]$, then $Q_{n\alpha}(f, x)$ converges uniformly to $f(x)$ on every finite subinterval of $[0, \infty)$.

Theorem 2.5. *Suppose $f^{(r)} \in C[0, \infty)$ ($0 \leq \alpha \leq r$, α integer). Then we have*

$$|f^{(i)}(x) - Q_{n\alpha}^{(i)}(f, x)| = O(1)\omega(f^{(r)}, n^{-\frac{1}{2}})n^{i-\frac{1}{2}r} \log n$$

for $1 \leq i \leq [\frac{1}{2}\alpha]$ and $0 \leq x \leq \Delta$.

3. Preliminaries and Lemmas

In order to prove our theorems, we need some known results:

$$(3.1) \quad x_k \sim k^2/n \quad (0 < x_k \leq 2\Delta) \quad [6, (8.9.10)]$$

$$(3.2) \quad |L_n^{(\alpha)}(x_k)| \sim x_k^{-\frac{1}{2}\alpha-3/4} n^{\frac{1}{2}\alpha+\frac{1}{4}} \sim k^{-\alpha-3/2} n^{\alpha+1} \quad [6, (8.9.11)]$$

$$(3.3-4) \quad L_n^{(\alpha)}(x) = \begin{cases} x^{-\frac{1}{2}\alpha-\frac{1}{4}} O(n^{\frac{1}{2}\alpha-\frac{1}{4}}), & \text{if } cn^{-1} \leq x \leq \Delta \\ O(n^\alpha), & \text{if } 0 \leq x \leq cn^{-1} \end{cases} \quad [6, (7.6.8)]$$

Lemma 3.1 [6, (14.7.5)]. *The following equation is valid:*

$$(3.5) \quad \sum_{k=1}^n x_k^{m-1} \left(L_n^{(\alpha)}(x_k) \right)^{-2} = \Gamma(n+1)\Gamma(m+\alpha+1)/\Gamma(n+\alpha+1) \\ (m \leq 2n+1)$$

Lemma 3.2 [7]. *Let*

$$(3.6) \quad |x - x_j| = \min_{1 \leq k \leq n} |x - x_k|.$$

Then for $0 \leq x, x_k \leq 2\Delta$,

$$(3.7) \quad |x - x_k| \sim |k^2 - j^2|/n \quad (k \neq j)$$

holds.

Lemma 3.3 [7]. *If $cn^{-1} \leq x \leq 2\Delta$, then*

$$(3.8) \quad x \sim j^2/n,$$

where j is defined by (3.6).

Lemma 3.4. *The following estimate is valid for $\alpha > -1$:*

$$(3.9) \quad x^{\frac{1}{2}\alpha + \frac{1}{4}} |L_n^{(\alpha)}(x)| = O(n^{\frac{1}{2}\alpha - \frac{1}{4}}), \quad 0 \leq x \leq 2\Delta.$$

PROOF. (3.9) follows from (3.3)–(3.4). $\square$

Lemma 3.5. *If $f \in C^r[0, \infty)$, then there exists a polynomial $G_n(f, x)$ of degree $n \geq 4r + 5$ such that*

$$(3.10) \quad |f^{(i)}(x) - G_n^{(i)}(f, x)| \\ = O(1)\omega(f^{(i)}, \sqrt{x(x_n - x)}/n)(\sqrt{x(x_n - x)}/n)^{r-i}$$

for $0 \leq x \leq x_n$ and $i = 1, \dots, r$.

The lemma is an obvious consequence of GOPENGAUZ's theorem [8].

4. Proofs of the Theorems

PROOF of Theorem 2.1. Set $x_0 = 0$. If $x = x_k$ ($k = 0, 1, \dots, n$), (2.1) holds obviously. Now suppose $x \neq x_k$ ($k = 0, 1, \dots, n$). Since

$$Q_{n\alpha}(1, x) = \sum_{k=1}^n l_k(x)(x/x_k)^{\alpha+1} + r_0(x) = 1,$$

observing that for $x_m \leq x < x_{m+1}$ ($0 \leq m \leq n-1$)

$$\text{sign } l_k(x) = \begin{cases} (-1)^{m+k+1}, & k > m \\ (-1)^{m+k}, & k \leq m, \end{cases}$$

where $l_0(x)$ means $r_0(x)$, then we have

$$\begin{aligned}
 \Lambda_n^{(\alpha)}(x) - 1 &= \sum_{k=1}^n |l_k(x)|(x/x_k)^{\alpha+1} + \sum_{i=0}^{\alpha} |r_i(x)| \\
 &\quad - \sum_{k=1}^n l_k(x)(x/x_k)^{\alpha+1} - r_0(x) \\
 &= \sum_{k=1}^n (|l_k(x)| - l_k(x))(x/x_k)^{\alpha+1} + \sum_{i=0}^{\alpha} |r_i(x)| - r_0(x) \\
 (4.1) \quad &= \sum_{k=1}^{m-1} (1 - (-1)^{m+k}) |l_k(x)|(x/x_k)^{\alpha+1} \\
 &\quad + \sum_{k=m+2}^n (1 - (-1)^{m+k+1}) |l_k(x)|(x/x_k)^{\alpha+1} \\
 &\quad + \left(\sum_{i=0}^{\alpha} |r_i(x)| - r_0(x) \right) := R_1 + R_2 + R_3.
 \end{aligned}$$

First suppose $x_1 \leq x \leq \Delta$. We have $m = 0(\sqrt{n})$ and $j = 0(\sqrt{n})$. Write

$$(4.2) \quad R_2 = \left(\sum_{x_k \leq 2\Delta} + \sum_{x_k > 2\Delta} \right) (1 - (-1)^{m+k+1}) |l_k(x)|(x/x_k)^{\alpha+1} := R_{21} + R_{22}.$$

For R_{21} , using (3.1)–(3.2) and (3.7), we get

$$\begin{aligned}
 R_{21} &\sim nx^{\alpha+1} |L_n^{(\alpha)}(x)| \sum_{m+2 \leq k \leq c\sqrt{n}} k^{-\alpha-\frac{1}{2}} |k^2 - j^2|^{-1} \\
 (4.3) \quad &= nx^{\alpha+1} |L_n^{(\alpha)}(x)| \left(\sum_{m+2 \leq k \leq 2j} + \sum_{2j+1 \leq k \leq c\sqrt{n}} \right)
 \end{aligned}$$

$$(4.4) \quad := R'_{21} + R''_{21}.$$

If $2j < m+2$, R'_{21} vanishes. Since $j \leq m+2 \leq k \leq 2j$, using (3.8), it follows that

$$\begin{aligned}
 R'_{21} &\sim nx^{\alpha+1} |L_n^{(\alpha)}(x)| j^{-\alpha-3/2} \sum_{m+2 \leq k \leq 2j} |k-j|^{-1} \\
 &\sim nx^{\alpha+1} j^{-\alpha-3/2} |L_n^{(\alpha)}(x)| \log j \\
 (4.5) \quad &\sim n^{-\frac{1}{2}\alpha+\frac{1}{4}} x^{\frac{1}{2}\alpha+\frac{1}{4}} |L_n^{(\alpha)}(x)| |\log(nx)|
 \end{aligned}$$

and

$$\begin{aligned}
 (4.6) \quad R_{21}'' &\sim nx^{\alpha+1} |L_n^{(\alpha)}(x)| \sum_{2j+1 \leq k \leq c\sqrt{n}} k^{-\alpha-5/2} \\
 &\sim nx^{\alpha+1} |L_n^{(\alpha)}(x)| j^{-\alpha-3/2} \sim n^{-\frac{1}{2}\alpha+\frac{1}{4}} x^{\frac{1}{2}\alpha+\frac{1}{4}} |L_n^{(\alpha)}(x)|.
 \end{aligned}$$

Combining (4.4)–(4.6) yields

$$(4.7) \quad R_{21} \sim n^{-\frac{1}{2}\alpha+\frac{1}{4}} x^{\frac{1}{2}\alpha+\frac{1}{4}} |L_n^{(\alpha)}(x)| (|\log(nx)| + 1).$$

For R_{22} , using (3.5), we get

$$\begin{aligned}
 (4.8) \quad R_{22} &\leq cx^{\alpha+1} |L_n^{(\alpha)}(x)| \sum_{x_k \geq 2\Delta} x_k^{-\alpha-2} |L_n^{(\alpha)}(x_k)|^{-1} \\
 &\leq cx^{\alpha+1} |L_n^{(\alpha)}(x)| \left(\sum_{x_k \geq 2\Delta} x_k^{-1} \left(L_n^{(\alpha)}(x_k) \right)^{-2} \right)^{\frac{1}{2}} \left(\sum_{k \geq c\sqrt{n}} x_k^{-2\alpha-3} \right)^{\frac{1}{2}} \\
 &\leq cn^{\frac{1}{4}-\frac{1}{2}\alpha} x^{\alpha+1} |L_n^{(\alpha)}(x)| \leq cn^{\frac{1}{4}-\frac{1}{2}\alpha} x^{\frac{1}{4}+\frac{1}{2}\alpha} |L_n^{(\alpha)}(x)|.
 \end{aligned}$$

Then combining (4.2) and (4.7)–(4.8) yields

$$(4.9) \quad R_2 \sim n^{\frac{1}{4}-\frac{1}{2}\alpha} x^{\frac{1}{4}+\frac{1}{2}\alpha} |L_n^{(\alpha)}(x)| (|\log(nx)| + 1).$$

For R_1 , we have

$$\begin{aligned}
 (4.10) \quad R_1 &\leq 2x^{\alpha+1} |L_n^{(\alpha)}(x)| \sum_{k=1}^{m-1} (x_k^{\alpha+1} |L_n^{(\alpha)}(x_k)| |x - x_k|)^{-1} \\
 &\leq cnx^{\alpha+1} |L_n^{(\alpha)}(x)| \sum_{k=1}^{m-1} k^{-\alpha-3/2} |k - j|^{-1} \\
 &\leq cnx^{\alpha+1} |L_n^{(\alpha)}(x)| \left(\sum_{k=1}^{[\frac{1}{2}j]} + \sum_{[\frac{1}{2}j]+1 \leq k \leq m-1} \right) \\
 &\leq cnx^{\alpha+1} |L_n^{(\alpha)}(x)| \left(j^{-\alpha-3/2} + j^{-\alpha-3/2} \log j \right) \\
 &\leq cn^{-\frac{1}{2}\alpha+\frac{1}{4}} x^{\frac{1}{2}\alpha+\frac{1}{4}} |L_n^{(\alpha)}(x)| |\log(nx)|.
 \end{aligned}$$

It is clear that

$$(4.11) \quad R_3 \leq cn^{-\alpha} |L_n^{(\alpha)}(x)| \sum_{i=0}^{\alpha} x^i / i! = o(n^{-\alpha} |L_n^{(\alpha)}(x)|).$$

Combining (4.1) and (4.9)–(4.11) yields (2.1) for $x \geq x_1$.

If $0 < x < x_1$, R_1 vanishes in (4.1) and $j = 1$. From (4.3) and (4.8) we obtain

$$(4.12) \quad R_{21} \sim nx^{\alpha+1} |L_n^{(\alpha)}(x)| \sum_{2 \leq k \leq c\sqrt{n}} (k^2 - 1)^{-1} k^{-\alpha - \frac{1}{2}} \sim nx^{\alpha+1} |L_n^{(\alpha)}(x)|$$

and

$$(4.13) \quad R_{22} \sim n^{\frac{1}{4} - \frac{1}{2}\alpha} x^{\alpha+1} |L_n^{(\alpha)}(x)| \leq nx^{\alpha+1} |L_n^{(\alpha)}(x)|.$$

Hence

$$(4.14) \quad R_2 \sim nx^{\alpha+1} |L_n^{(\alpha)}(x)|.$$

Observing that $r_0(x)$ vanishes in this case, it is obvious that

$$(4.15) \quad R_3 \sim n^{-\alpha} x |L_n^{(\alpha)}(x)|.$$

Finally, collecting (4.1) and (4.14)–(4.15) implies

$$(\Lambda_n^{(\alpha)}(x) - 1) \sim x |L_n^{(\alpha)}(x)| (nx^\alpha + n^{-\alpha}) \quad (0 \leq x \leq x_1). \quad \square$$

PROOF of Theorem 2.3. Applying (3.10) and the fact $x_n \leq cn$, we have

$$|f^{(i)}(x) - G_n^{(i)}(f, x)| = 0(1) \omega(f^{(r)}, \sqrt{x/n}) (\sqrt{x/n})^{r-i}.$$

Observing the invariability of Hermite interpolation (1.2) for a polynomial of degree $\leq n + \alpha$, we obtain

$$\begin{aligned} |f(x) - Q_{n\alpha}(f, x)| &\leq |f(x) - G_{n+\alpha}(f, x)| + |G_{n+\alpha}(f, x) - Q_{n\alpha}(f, x)| \\ &= 0(1) \left\{ \omega(f^{(r)}, \sqrt{x/n}) (\sqrt{x/n})^r \right. \\ &\quad \left. + \sum_{k=1}^n |f(x_k) - G_{n+\alpha}(f, x_k)| |l_k(x)| (x/x_k)^{\alpha+1} \right\} \\ &= 0(1) \left\{ \omega(f^{(r)}, n^{-\frac{1}{2}}) (x/n)^{\frac{1}{2}r} \right. \\ &\quad \left. + \sum_{k=1}^n \omega(f^{(r)}, \sqrt{x_k/n}) (\sqrt{x_k/n})^r |l_k(x)| (x/x_k)^{\alpha+1} \right\} \end{aligned}$$

$$\begin{aligned}
&= 0(1)\omega(f^{(r)}, n^{-\frac{1}{2}}) \left\{ (x/n)^{\frac{1}{2}r} \right. \\
&\quad \left. + \sum_{k=1}^n (1+x_k^{\frac{1}{2}})(x_k/n)^{\frac{1}{2}r} |l_k(x)|(x/x_k)^{\alpha+1} \right\} \\
&= 0(1)\omega(f^{(r)}, n^{-\frac{1}{2}}) \left\{ (x/n)^{\frac{1}{2}r} + \sum_{0 < x_k \leq 2\Delta} + \sum_{x_k > 2\Delta} \right\} \\
(4.16) \quad &:= 0(1)\omega(f^{(r)}, n^{-\frac{1}{2}}) \left\{ (x/n)^{\frac{1}{2}r} + r_1 + r_2 \right\}.
\end{aligned}$$

Noting that $x_k \leq 2\Delta$ and using (3.1)–(3.2) and (3.7), it follows

$$\begin{aligned}
r_1 &= 0(x^{\alpha+1})n^{-\frac{1}{2}r} |L_n^{(\alpha)}(x)| \sum_{\substack{0 < x_k \leq 2\Delta \\ k \neq j}} x_k^{\frac{1}{2}r-\alpha-1} (|L_n^{(\alpha)}(x_k)(x-x_k)|)^{-1} \\
(4.17) \quad &+ n^{-\frac{1}{2}r} x^{\alpha+1} x_j^{\frac{1}{2}r-\alpha-1} |l_j(x)| := r_{11} + r_{12},
\end{aligned}$$

and

$$\begin{aligned}
r_{11} &= 0(x^{\alpha+1})n^{1-r} |L_n^{(\alpha)}(x)| \sum_{k=1, k \neq j}^{[cn^{\frac{1}{2}}]} k^{r-\alpha-\frac{1}{2}} |k^2 - j^2|^{-1} \\
&= 0(x^{\alpha+1})n^{1-r} |L_n^{(\alpha)}(x)| \left(\sum_{k=1}^{[\frac{1}{2}j]} + \sum_{k=[\frac{1}{2}j]+1, k \neq j}^{2j} + \sum_{k=2j+1}^{[cn^{\frac{1}{2}}]} \right) \\
&= 0(x^{\alpha+1})n^{1-r} |L_n^{(\alpha)}(x)| (j^{r-\alpha-3/2} + j^{r-\alpha-3/2} \log j + \\
&\quad + \max(n^{\frac{1}{2}r-\frac{1}{2}\alpha-3/4}, j^{r-\alpha-3/2})) \\
&= \begin{cases} 0(x^{\frac{1}{2}r} n^{-\frac{1}{2}r} \log n), & \text{if } r - \alpha - 3/2 \leq 0 \\ 0(x^{\frac{1}{2}\alpha+3/4} n^{-\frac{1}{2}r} + x^{\frac{1}{2}r} n^{-\frac{1}{2}r} \log n), & \text{if } r - \alpha - 3/2 > 0 \end{cases} \\
(4.18) \quad &= 0(n^{-\frac{1}{2}r} \log n)(x^{\frac{1}{2}r} + x^{\frac{1}{2}\alpha+3/4}).
\end{aligned}$$

For r_{12} , if $x \geq c/n$, using Lemma 3.3 and the fact $x_j \sim x$ and $l_j(x) = 0(1)$, we get

$$r_{12} = 0(x^{\frac{1}{2}r} n^{-\frac{1}{2}r}) \quad (x \geq c/n).$$

If $0 \leq x < c/n$, then $j = 1$ and

$$(4.19) \quad \begin{aligned} r_{12} &= 0(x^{\alpha+1})|L_n^{(\alpha)}(x)|n^{1-r} = 0(x^{\frac{1}{2}\alpha+3/4})(n^{-\frac{1}{2}r}n^{-\frac{1}{2}r+\frac{1}{2}\alpha+3/4}) \\ &= 0(n^{-\frac{1}{2}r})(x^{\frac{1}{2}r} + x^{\frac{1}{2}\alpha+3/4}) \quad (x < c/n). \end{aligned}$$

Combining (4.17)–(4.19) yields

$$(4.20) \quad r_1 = 0(n^{-\frac{1}{2}r} \log n)(x^{\frac{1}{2}r} + x^{\frac{1}{2}\alpha+3/4}).$$

Collecting (2.1), (3.5) and (3.9), we get

$$(4.21) \quad \begin{aligned} r_2 &= 0(x^{\alpha+1})|L_n^{(\alpha)}(x)|n^{-\frac{1}{2}r} \sum_{x_k > 2\Delta} x_k^r (x_k^{\alpha+3/2} |L_n^{(\alpha)}(x_k)|)^{-1} \\ &= 0(x^{\alpha+1}n^{-\frac{1}{2}r})|L_n^{(\alpha)}(x)| \left(\sum_{k=1}^n x_k^{2r} (L_n^{(\alpha)}(x_k))^{-2} \right)^{\frac{1}{2}} \left(\sum_{k > [cn^{\frac{1}{2}}]} x_k^{-2\alpha-3} \right)^{\frac{1}{2}} \\ &= 0(x^{\frac{1}{2}\alpha+3/4}n^{-\frac{1}{2}r}). \end{aligned}$$

Finally, collecting (4.16) and (4.20)–(4.21) yields (2.3). $\square$

PROOF of Theorem 2.5. Since the proof is similar to [5], we omit the detail. $\square$

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