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in non-archimedean fields**

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Silvermann-Toeplitz theorem for double sequences and series and its application to Nörlund means in non-archimedean fields

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Abstract

In this paper, K denotes a complete, non-trivially valued, non-archimedean field. The entries of sequences, series and infinite matrices are in K . In the present paper, we prove the Silvermann-Toeplitz theorem for double sequences and series in K and apply it to Nörlund means for double sequences and series in K .

Throughout the present paper, K denotes a complete, non-trivially valued, non-archimedean field. The entries of sequences, series and infinite matrices are in K . In this paper, we prove the Silvermann-Toeplitz theorem for double sequences and series in K (see Theorem 2, proved in the sequel). We then introduce Nörlund means for double sequences and series in K and apply Silvermann-Toeplitz theorem for these means.

For analysis in the classical case a general reference is [2] while for analysis in non-archimedean fields a general reference is [1].

For a given infinite matrix $A = (a_{n,k})$ and a sequence $\{x_k\}$, the sequence $\{y_n\}$ is defined as follows:

$$y_n = \sum_{k=1}^{\infty} a_{n,k} x_k, \quad n = 1, 2, \dots,$$

it being assumed that the series on the right converge. If $\lim_{n \rightarrow \infty} y_n = s$ whenever $\lim_{k \rightarrow \infty} x_k = s$, we say that A is regular. The criterion for A to be regular in terms of the entries of the matrix A are well-known (see [4], [6]).

Theorem 1. $A = (a_{n,k})$ is regular if and only if

- (i) $\sup_{n,k} |a_{n,k}| < \infty$;

$$(ii) \lim_{n \rightarrow \infty} a_{n,k} = 0, k = 1, 2, \dots;$$

and

$$(iii) \lim_{n \rightarrow \infty} \sum_{k=1}^{\infty} a_{n,k} = 1.$$

In the sequel, the following definitions are needed.

Definition 1. Let $\{x_{m,n}\}$ be a double sequence in K and $x \in K$. We say that $\lim_{m+n \rightarrow \infty} x_{m,n} = x$ if for each $\epsilon > 0$, the set $\{(m, n) \in \mathbb{N}^2 : |x - x_{m,n}| \geq \epsilon\}$ is finite. In such a case we say that x is the limit of $\{x_{m,n}\}$.

Definition 2. Let $\{x_{m,n}\}$ be a double sequence in K and $s \in K$. We say that

$$s = \sum_{m=1, n=1}^{\infty, \infty} x_{m,n},$$

if

$$s = \lim_{m+n \rightarrow \infty} s_{m,n},$$

where

$$s_{m,n} = \sum_{k=1, l=1}^{m, n} x_{k,l}, m, n = 1, 2, \dots.$$

Remark. If $\lim_{m+n \rightarrow \infty} x_{m,n} = x$, then the sequence $\{x_{m,n}\}$ is automatically bounded.

It is easy to prove the following results.

Lemma 1. $\lim_{m+n \rightarrow \infty} x_{m,n} = x$ if and only if

$$(i) \lim_{n \rightarrow \infty} x_{m,n} = x, m = 1, 2, \dots,$$

$$(ii) \lim_{m \rightarrow \infty} x_{m,n} = x, n = 1, 2, \dots,$$

and

$$(iii) \text{ for each } \epsilon > 0 \text{ there exists an } N \in \mathbb{N} \text{ such that } |x - x_{m,n}| < \epsilon, \text{ for all } m, n \geq N, \text{ which we write as } \lim_{m, n \rightarrow \infty} x_{m,n} = x.$$

Lemma 2. $\lim_{m+n \rightarrow \infty} s_{m,n}$ exists if and only if

$$\lim_{m+n \rightarrow \infty} x_{m,n} = 0. \quad (1)$$

Given the matrix $A = (a_{m,n,k,l})$, we define

$$y_{m,n} = \sum_{k=1, l=1}^{\infty, \infty} a_{m,n,k,l} x_{k,l}, \quad m, n = 1, 2, \dots, \quad (2)$$

assuming that the series on the right converge.

Necessary and sufficient conditions for $A = (a_{m,n,k,l})$ to be regular for the class of all double sequences and series in the classical case have been found by Kojima [3]. It has been found that convergence and boundedness play a vital role for double sequences and series, a role analogous to that of convergence for simple sequences and series. Robison [8] proved Silvermann-Toeplitz theorem for such a class of bounded and convergent double sequences in the classical case. We prove here its analogue in a complete, non-trivially valued, non-archimedean field.

In this context, the following definition is needed.

Definition 3. If whenever $\{x_{m,n}\}$ is a convergent sequence, $\{y_{m,n}\}$ converges to the same value, then the matrix $A = (a_{m,n,k,l})$ is said to be regular.

Theorem 2. *In order that whenever a sequence $\{x_{m,n}\}$ has a limit x , $\sum_{k=1, l=1}^{\infty, \infty} a_{m,n,k,l} x_{k,l}$ shall converge and $\lim_{m+n \rightarrow \infty} \sum_{k=1, l=1}^{\infty, \infty} a_{m,n,k,l} x_{k,l} = x$, i.e., for $A = (a_{m,n,k,l})$ to be regular it is necessary and sufficient that*

$$(a) \quad \lim_{m+n \rightarrow \infty} a_{m,n,k,l} = 0, \quad k, l = 1, 2, \dots;$$

$$(b) \quad \lim_{m+n \rightarrow \infty} \sum_{k=1, l=1}^{\infty, \infty} a_{m,n,k,l} = 1;$$

$$(c) \quad \lim_{m+n \rightarrow \infty} \sup_{k \geq 1} |a_{m,n,k,l}| = 0, \quad l = 1, 2, \dots;$$

$$(d) \quad \lim_{m+n \rightarrow \infty} \sup_{l \geq 1} |a_{m,n,k,l}| = 0, \quad k = 1, 2, \dots;$$

and

$$(e) \sup_{m,n,k,l} |a_{m,n,k,l}| < \infty.$$

Proof. Proof of necessity.

Define the sequence $\{x_{k,l}\}$ as follows: For any fixed p, q , let

$$x_{k,l} = \begin{cases} 1, & \text{when } k = p, l = q; \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

Then

$$y_{m,n} = a_{m,n,p,q}.$$

Since $\{x_{k,l}\}$ has limit 0, it follows that (a) is necessary.

Define the sequence $\{x_{k,l}\}$ where $x_{k,l} = 1, k, l = 1, 2, \dots$.

Now,

$$y_{m,n} = \sum_{k=1, l=1}^{\infty, \infty} a_{m,n,k,l}, \quad m, n = 1, 2, \dots$$

$$\text{This shows that } \sum_{k=1, l=1}^{\infty, \infty} a_{m,n,k,l} \text{ converges for } m, n = 1, 2, \dots \quad (4)$$

Since $\{x_{k,l}\}$ has limit 1, it follows that

$$\lim_{m+n \rightarrow \infty} \sum_{k=1, l=1}^{\infty, \infty} a_{m,n,k,l} = 1,$$

so that (b) is necessary.

We now show that $\lim_{m+n \rightarrow \infty} \sup_{k \geq 1} |a_{m,n,k,l}| = 0$ for all $l \in \mathbb{N}$. Suppose not.

Then there exists $l_0 \in \mathbb{N}$ such that $\lim_{m+n \rightarrow \infty} \sup_{k \geq 1} |a_{m,n,k,l_0}| = 0$ does not hold.

So, there exists an $\epsilon > 0$, such that

$$\left\{ (m, n) : \sup_{k \geq 1} |a_{m,n,k,l_0}| > \epsilon \right\} \text{ is infinite.} \quad (5)$$

Let us choose $m_1 = n_1 = r_1 = 1$. Choose $m_2, n_2 \in \mathbb{N}$ such that $m_2 + n_2 > m_1 + n_1$ and

$$\sup_{1 \leq k \leq r_1} |a_{m_2, n_2, k, l_0}| < \frac{\epsilon}{8}, \text{ using (a);}$$

and

$$\sup_{k \geq 1} |a_{m_2, n_2, k, l_0}| > \epsilon, \text{ using (5).}$$

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Then choose $r_2 \in \mathbb{N}$ such that $r_2 > r_1$ and

$$\sup_{k > r_2} |a_{m_2, n_2, k, l_0}| < \frac{\epsilon}{8}, \text{ using (b).}$$

Inductively choose $m_p + n_p > m_{p-1} + n_{p-1}$ such that

$$\sup_{1 \leq k \leq r_{p-1}} |a_{m_p, n_p, k, l_0}| < \frac{\epsilon}{8}; \quad (6)$$

$$\sup_{k \geq 1} |a_{m_p, n_p, k, l_0}| > \epsilon; \quad (7)$$

and then choose $r_p > r_{p-1}$ such that

$$\sup_{k > r_p} |a_{m_p, n_p, k, l_0}| < \frac{\epsilon}{8}. \quad (8)$$

In view of (6), (7), (8), we have

$$\sup_{r_{p-1} < k \leq r_p} |a_{m_p, n_p, k, l_0}| > \epsilon - \frac{\epsilon}{8} - \frac{\epsilon}{8} = \frac{3\epsilon}{4}.$$

We can now find $k_p \in \mathbb{N}$, $r_{p-1} < k_p \leq r_p$ such that

$$|a_{m_p, n_p, k_p, l_0}| > \frac{3\epsilon}{4}. \quad (9)$$

Define the sequence $\{x_{k,l}\}$ as follows:

$$x_{k,l} = \begin{cases} 0, & l \neq l_0; \\ 1, & \text{if } l = l_0, k = k_p, p = 1, 2, \dots \end{cases}$$

We note that $\lim_{k+l \rightarrow \infty} x_{k,l} = 0$. Now, in view of (6),

$$\left| \sum_{k=1}^{r_{p-1}} a_{m_p, n_p, k, l_0} x_{k, l_0} \right| \leq \sup_{1 \leq k \leq r_{p-1}} |a_{m_p, n_p, k, l_0}| < \frac{\epsilon}{8}; \quad (10)$$

Using (8), we have,

$$\left| \sum_{k=r_p+1}^{\infty} a_{m_p, n_p, k, l_0} x_{k, l_0} \right| \leq \sup_{k > r_p} |a_{m_p, n_p, k, l_0}| < \frac{\epsilon}{8}; \quad (11)$$

and using (9), we get,

$$\left| \sum_{k=r_{p-1}+1}^{r_p} a_{m_p, n_p, k, l_0} x_{k, l_0} \right| = |a_{m_p, n_p, k_p, l_0}| > \frac{3\epsilon}{4}. \quad (12)$$

Thus

$$\begin{aligned} |y_{m_p, n_p}| &= \left| \sum_{k=1}^{\infty} a_{m_p, n_p, k, l_0} x_{k, l_0} \right| \\ &\geq \left| \sum_{k=r_{p-1}+1}^{r_p} a_{m_p, n_p, k, l_0} x_{k, l_0} \right| - \left| \sum_{k=1}^{r_{p-1}} a_{m_p, n_p, k, l_0} x_{k, l_0} \right| - \left| \sum_{k=r_p+1}^{\infty} a_{m_p, n_p, k, l_0} x_{k, l_0} \right| \\ &\geq |a_{m_p, n_p, k_p, l_0}| - \sup_{1 \leq k \leq r_{p-1}} |a_{m_p, n_p, k, l_0}| - \sup_{k > r_p} |a_{m_p, n_p, k, l_0}| \\ &> \frac{3\epsilon}{4} - \frac{\epsilon}{8} - \frac{\epsilon}{8}, \text{ using (10), (11) and (12)} \\ &= \frac{\epsilon}{2}, \quad p = 1, 2, \dots \end{aligned}$$

Consequently $\lim_{m+n \rightarrow \infty} y_{m, n} = 0$ does not hold, which is a contradiction. Thus

(c) is necessary. The necessity of (d) follows in a similar fashion.

To establish (e), we shall suppose that (e) does not hold and arrive at a contradiction. Since K is non-trivially valued, there exists $\pi \in K$ such that $0 < \rho = |\pi| < 1$. Choose $m_1 = n_1 = 1$. Using (a), (b), choose $m_2 + n_2 > m_1 + n_1$ such that

$$\sup_{1 \leq k+l \leq m_1+n_1} |a_{m_2, n_2, k, l}| < 2, \text{ using (a);}$$

$$\sup_{k+l \geq 1} |a_{m_2, n_2, k, l}| > \left(\frac{2}{\rho}\right)^6;$$

and

$$\sup_{k+l > m_1+n_1} |a_{m_2, n_2, k, l}| < 2^2, \text{ using (b) and Lemma 1, Lemma 2.}$$

It now follows that

$$\sup_{k+l > m_2+n_2} |a_{m_2, n_2, k, l}| < 2^2.$$

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Choose $m_3 + n_3 > m_2 + n_2$ such that

$$\sup_{1 \leq k+l \leq m_2+n_2} |a_{m_3, n_3, k, l}| < 2^2;$$

$$\sup_{k+l \geq 1} |a_{m_3, n_3, k, l}| > \left(\frac{2}{\rho}\right)^8;$$

and

$$\sup_{k+l > m_3+n_3} |a_{m_3, n_3, k, l}| < 2^4.$$

Inductively, choose $m_p + n_p > m_{p-1} + n_{p-1}$, such that

$$\sup_{1 \leq k+l \leq m_{p-1}+n_{p-1}} |a_{m_p, n_p, k, l}| < 2^{p-1}; \quad (13)$$

$$\sup_{k+l \geq 1} |a_{m_p, n_p, k, l}| > \left(\frac{2}{\rho}\right)^{2p+2} \quad (14)$$

and

$$\sup_{k+l > m_p+n_p} |a_{m_p, n_p, k, l}| < 2^{2p-2}. \quad (15)$$

Using (13), (14), (15), we have,

$$\begin{aligned} & \sup_{m_{p-1}+n_{p-1} < k+l \leq m_p+n_p} |a_{m_p, n_p, k, l}| > \left(\frac{2}{\rho}\right)^{2p+2} - 2^{2p-2} - 2^{p-1} \\ & \geq \left(\frac{2}{\rho}\right)^{2p+2} - \left(\frac{2}{\rho}\right)^{2p-2} - \left(\frac{2}{\rho}\right)^{p-1}, \text{ since } \frac{1}{\rho} > 1 \\ & = \left(\frac{2}{\rho}\right)^{p-1} \left[\left(\frac{2}{\rho}\right)^{p+3} - \left(\frac{2}{\rho}\right)^{p-1} - 1 \right] \\ & \geq \left(\frac{2}{\rho}\right)^{p-1} \left[\left(\frac{2}{\rho}\right)^{p+3} - \left(\frac{2}{\rho}\right)^{p-1} - \left(\frac{2}{\rho}\right)^{p-1} \right], \text{ since } \left(\frac{2}{\rho}\right)^{p-1} \geq 1 \\ & = \left(\frac{2}{\rho}\right)^{p-1} \left[\left(\frac{2}{\rho}\right)^4 \left(\frac{2}{\rho}\right)^{p-1} - 2 \left(\frac{2}{\rho}\right)^{p-1} \right], \\ & > \left(\frac{2}{\rho}\right)^{p-1} \left[\left(\frac{2}{\rho}\right)^4 \left(\frac{2}{\rho}\right)^{p-1} - \left(\frac{2}{\rho}\right) \left(\frac{2}{\rho}\right)^{p-1} \right], \text{ since } \frac{2}{\rho} > 2 \end{aligned}$$

$$\begin{aligned}
 &= \left(\frac{2}{\rho}\right)^{2p-1} \left[\left(\frac{2}{\rho}\right)^3 - 1 \right] \\
 &> \left(\frac{2}{\rho}\right)^{2p-1} [2^3 - 1], \text{ since } \frac{2}{\rho} > 2 \\
 &= 7 \left(\frac{2}{\rho}\right)^{2p-1} \\
 &> 4 \left(\frac{2}{\rho}\right)^{2p-1} \\
 &= \frac{2^{2p+1}}{\rho^{2p-1}} \\
 &> \frac{2^{2p+1}}{\rho^p}, \text{ since } \frac{1}{\rho} > 1.
 \end{aligned} \tag{16}$$

Thus there exist k_p and l_p , $m_{p-1} + n_{p-1} < k_p + l_p \leq m_p + n_p$ such that

$$|a_{m_p, n_p, k_p, l_p}| > \frac{2^{2p+1}}{\rho^p}. \tag{17}$$

Now, define the sequence $\{x_{k,l}\}$ as follows:

$$x_{k,l} = \begin{cases} \pi^p, & \text{if } k = k_p, l = l_p, p = 1, 2, \dots; \\ 0, & \text{otherwise.} \end{cases}$$

We note that $\lim_{k+l \rightarrow \infty} x_{k,l} = 0$. Now,

$$\begin{aligned}
 |y_{m_p, n_p}| &= \left| \sum_{k=1, l=1}^{\infty, \infty} a_{m_p, n_p, k, l} x_{k, l} \right| \\
 &\geq \left| \sum_{k+l=(m_{p-1}+n_{p-1})+1}^{m_p+n_p} a_{m_p, n_p, k, l} x_{k, l} \right| \\
 &\quad - \left| \sum_{k+l=1}^{m_{p-1}+n_{p-1}} a_{m_p, n_p, k, l} x_{k, l} \right| \\
 &\quad - \left| \sum_{k+l=(m_p+n_p)+1}^{\infty} a_{m_p, n_p, k, l} x_{k, l} \right|
 \end{aligned}$$

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$$\begin{aligned}
&\geq |a_{m_p, n_p, k_p, l_p}| \times |x_{k_p, l_p}| - \\
&\quad \sup_{1 \leq k+l \leq m_{p-1} + n_{p-1}} |a_{m_p, n_p, k, l}| - \sup_{m_p + n_p < k+l < \infty} |a_{m_p, n_p, k, l}| \\
&> \frac{2^{2p+1}}{\rho^p} \rho^p - 2^{2p-2} - 2^{p-1}, \text{ using (13), (15) and (17)} \\
&= 2^{2p+1} - 2^{2p-2} - 2^{p-1} \\
&= 2^{2p-2}(2^3 - 1) - 2^{p-1} \\
&= 2^{2p-2}(7) - 2^{p-1} \\
&= 2^{p-1}[7 \cdot 2^{p-1} - 1] \\
&\geq 2^{p-1}[7 \cdot 2^{p-1} - 2^{p-2}] \\
&= 2^{p-1}[2^{p-2}(14 - 1)] \\
&= 2^{p-1}[13 \cdot 2^{p-2}] \\
&= 13 \cdot 2^{2p-3}
\end{aligned}$$

i.e., $|y_{m_p, n_p}| > 13 \cdot 2^{2p-3}$, $p = 1, 2, \dots$,

i.e., $\lim_{m+n \rightarrow \infty} y_{mn} = 0$ does not hold, which is a contradiction. Thus (e) is necessary.

Proof of Sufficiency.

Let $\lim_{m+n \rightarrow \infty} x_{m,n} = x$. Then

$$y_{m,n} - x = \sum_{k=1, l=1}^{\infty, \infty} a_{m,n,k,l} x_{k,l} - x.$$

From (b) we have

$$\sum_{k=1, l=1}^{\infty, \infty} a_{m,n,k,l} + r_{m,n} = 1,$$

where

$$\lim_{m+n \rightarrow \infty} r_{m,n} = 0. \quad (18)$$

Hence,

$$y_{m,n} - x = \sum_{k=1, l=1}^{\infty, \infty} a_{m,n,k,l} (x_{k,l} - x) + r_{m,n} x.$$

Given $\epsilon > 0$, we can choose sufficiently large p and q such that

$$\sup_{k+l > p+q} |x_{k,l} - x| < \frac{\epsilon}{5H}, \quad (19)$$

where $H = \sup_{m,n,k,l \geq 1} |a_{m,n,k,l}|$. Observe that $H > 0$ (from (b)).

Let $L = \sup_{k+l \geq 1} |x_{k,l} - x|$. We now choose $N \in \mathbb{N}$ such that whenever $m+n \geq N$, the following are satisfied:

$$(i) \sup_{1 \leq k+l \leq p+q} |a_{m,n,k,l}| < \frac{\epsilon}{5pqL}, \text{ using (a);} \quad (20)$$

$$(ii) \sup_{k \geq 1} |a_{m,n,k,l}| < \frac{\epsilon}{5qL}, \quad l = 1, 2, \dots, q, \text{ using (c);} \quad (21)$$

$$(iii) \sup_{l \geq 1} |a_{m,n,k,l}| < \frac{\epsilon}{5pL}, \quad k = 1, 2, \dots, p, \text{ using (d);} \quad (22)$$

and

$$(iv) |r_{m,n}| < \frac{\epsilon}{5|x|}, \text{ from the equation (18).} \quad (23)$$

Whenever $m+n \geq N$, we thus have,

$$\begin{aligned} |y_{m,n} - x| &= \left| \sum_{k=1, l=1}^{\infty, \infty} a_{m,n,k,l} (x_{k,l} - x) + r_{m,n} x \right| \\ &\leq \left| \sum_{k=1, l=1}^{p,q} a_{m,n,k,l} (x_{k,l} - x) \right| + \left| \sum_{k=1, l=q+1}^{p, \infty} a_{m,n,k,l} (x_{k,l} - x) \right| \\ &\quad + \left| \sum_{k=p+1, l=1}^{\infty, q} a_{m,n,k,l} (x_{k,l} - x) \right| + \left| \sum_{k=p+1, l=q+1}^{\infty, \infty} a_{m,n,k,l} (x_{k,l} - x) \right| \\ &\quad + |r_{m,n}| |x| \\ &< \frac{\epsilon}{5pqL} Lpq + \frac{\epsilon}{5pL} Lp + \frac{\epsilon}{5qL} Lq + \frac{\epsilon}{5H} H + \frac{\epsilon}{5|x|} |x| \\ &= \epsilon, \quad \text{using (19), (20), (21), (22) and (23).} \end{aligned}$$

Thus

$$\lim_{m+n \rightarrow \infty} y_{m,n} = x,$$

which completes the proof of the theorem.

Nörlund means for simple sequences and series in complete, non-trivially valued, non-archimedean fields were introduced by Srinivasan [9] and studied

later in detail by Natarajan (for instance, see [7]). Nörlund means for double sequences and series in classical analysis were introduced by Moore [5]. We now define Nörlund means for double sequences and series in complete, non-trivially valued, non-archimedean fields and apply Theorem 2 for these means.

Definition 4. Given a doubly infinite set of elements $p_{m,n} \in K$, $m, n = 0, 1, 2, \dots$, where $p_{0,0} \neq 0$, $|p_{i,j}| < |p_{0,0}|$, $(i, j) \neq (0, 0)$, $i, j = 0, 1, 2, \dots$, let

$$P_{m,n} = \sum_{i,j=0}^{m,n} p_{i,j}, \quad m, n = 0, 1, 2, \dots$$

Given any double sequence $\{s_{m,n}\}$ we define

$$\sigma_{m,n} = (N, p_{m,n})(s_{m,n}) = \frac{S_{m,n}}{P_{m,n}} = \frac{\sum_{i,j=0}^{m,n} p_{m-i,n-j} s_{i,j}}{P_{m,n}}, \quad m, n = 0, 1, 2, \dots$$

If $\lim_{m+n \rightarrow \infty} \sigma_{m,n} = \sigma$, we say that the double sequence $\{s_{m,n}\}$ is summable $(N, p_{m,n})$ to the value σ , written as

$$s_{m,n} \rightarrow \sigma(N, p_{m,n}).$$

Any double series $\sum_{m,n} u_{m,n}$ is said to be summable $(N, p_{m,n})$ to the value σ if the double sequence $\{s_{m,n}\}$, where

$$s_{m,n} = \sum_{i,j=0}^{m,n} u_{i,j}, \quad m, n = 0, 1, 2, \dots,$$

is summable $(N, p_{m,n})$ to the value σ .

Definition 5. Given the Nörlund means $(N, p_{m,n}), (N, q_{m,n})$, we say that they are consistent if

$$s_{m,n} \rightarrow \sigma(N, p_{m,n}) \text{ and } s_{m,n} \rightarrow \sigma'(N, q_{m,n}) \Rightarrow \sigma = \sigma'.$$

We say that $(N, p_{m,n})$ is included in $(N, q_{m,n})$, written as

$$(N, p_{m,n}) \subseteq (N, q_{m,n}),$$

if

$$s_{m,n} \rightarrow \sigma(N, p_{m,n}) \Rightarrow s_{m,n} \rightarrow \sigma(N, q_{m,n}).$$

The two methods $(N, p_{m,n}), (N, q_{m,n})$ are said to be equivalent if

$$(N, p_{m,n}) \subseteq (N, q_{m,n}) \text{ and } (N, q_{m,n}) \subseteq (N, p_{m,n}).$$

In view of Theorem 2, it is easy to prove the following result.

Theorem 3. *The necessary and sufficient conditions for the regularity of the Nörlund means $(N, p_{m,n})$ are:*

$$\lim_{m+n \rightarrow \infty} \sup_{0 \leq j \leq n} |p_{m-i, n-j}| = 0, \quad 0 \leq i \leq m; \quad (24)$$

$$\lim_{m+n \rightarrow \infty} \sup_{0 \leq i \leq m} |p_{m-i, n-j}| = 0, \quad 0 \leq j \leq n. \quad (25)$$

In the sequel let $(N, p_{m,n}), (N, q_{m,n})$ be two regular Nörlund methods such that each row and each column of the infinite matrices $(p_{m,n}), (q_{m,n})$ is a regular Nörlund mean for simple sequences.

Theorem 4. *Any two such regular Nörlund methods are consistent.*

Proof. Given two Nörlund methods $(N, p_{m,n})$ and $(N, q_{m,n})$, where each row and each column of the infinite matrices $(p_{m,n}), (q_{m,n})$ is a regular Nörlund mean for simple sequences, we define a third method $(N, r_{m,n})$ by the equation

$$r_{m,n} = \sum_{i,j=0}^{m,n} p_{i,j} q_{m-i, n-j}, \quad m, n = 0, 1, 2, \dots$$

We then readily obtain, for $s = \{s_{m,n}\}$,

$$(N, r_{m,n})(s) = \sum_{i,j=0}^{m,n} \gamma_{m,n,i,j} (N, q_{i,j})(s),$$

where

$$\gamma_{m,n,i,j} = p_{m-i, n-j} Q_{i,j} / \sum_{\mu, \nu=0}^{m,n} p_{m-\mu, n-\nu} Q_{\mu, \nu}.$$

Since $(N, p_{m,n})$ and $(N, q_{m,n})$ are regular, we have,

$$\lim_{m+n \rightarrow \infty} \sup_{0 \leq j \leq n} |p_{m-i, n-j}| = 0 = \lim_{m+n \rightarrow \infty} \sup_{0 \leq i \leq m} |p_{m-i, n-j}|.$$

SILVERMANN-TOEPLITZ THEOREM FOR DOUBLE SEQUENCES AND SERIES

It now follows that

$$\lim_{m+n \rightarrow \infty} \sup_{0 \leq j \leq n} \gamma_{m,n,i,j} = 0 = \lim_{m+n \rightarrow \infty} \sup_{0 \leq i \leq m} \gamma_{m,n,i,j}.$$

Consequently $(N, r_{m,n})$ is regular. The regularity of this transformation enables us to infer that

$$s_{m,n} \rightarrow \sigma'(N, q_{m,n}) \Rightarrow s_{m,n} \rightarrow \sigma'(N, r_{m,n}).$$

Similarly we can show that

$$s_{m,n} \rightarrow \sigma(N, p_{m,n}) \Rightarrow s_{m,n} \rightarrow \sigma(N, r_{m,n}).$$

These imply that the two Nörlund methods $(N, p_{m,n})$ and $(N, q_{m,n})$ are consistent, completing the proof of the theorem.

If $(N, p_{m,n})$, $(N, q_{m,n})$ are regular, in view of conditions (24), (25), we have,

$$\begin{aligned} P(x, y) &= \sum P_{m,n} x^m y^n, \\ Q(x, y) &= \sum Q_{m,n} x^m y^n, \\ p(x, y) &= \sum p_{m,n} x^m y^n, \\ q(x, y) &= \sum q_{m,n} x^m y^n, \end{aligned}$$

all converge for $|x|, |y| < 1$. The series

$$\begin{aligned} k(x, y) &= \sum k_{m,n} x^m y^n = \frac{q(x, y)}{p(x, y)} = \frac{Q(x, y)}{P(x, y)}, \\ l(x, y) &= \sum l_{m,n} x^m y^n = \frac{p(x, y)}{q(x, y)} = \frac{P(x, y)}{Q(x, y)} \end{aligned}$$

are convergent for $|x|, |y| < 1$ and further

$$\sum_{i,j=0}^{m,n} k_{i,j} p_{m-i,n-j} = q_{m,n}; \quad \sum_{i,j=0}^{m,n} k_{i,j} P_{m-i,n-j} = Q_{m,n}, \quad (26)$$

$$\sum_{i,j=0}^{m,n} l_{i,j} q_{m-i,n-j} = p_{m,n}; \quad \sum_{i,j=0}^{m,n} l_{i,j} Q_{m-i,n-j} = P_{m,n}. \quad (27)$$

Theorem 5. *If $(N, p_{m,n}), (N, q_{m,n})$ are regular, then $(N, p_{m,n}) \subseteq (N, q_{m,n})$ if and only if $\lim_{m+n \rightarrow \infty} k_{m,n} = 0$.*

Proof. Let $s(x, y) = \sum s_{m,n} x^m y^n$. Then for $|x|, |y| < 1$, we have,

$$\begin{aligned} \sum Q_{m,n}(N, q_{m,n})(s) x^m y^n &= \sum \left(\sum_{i,j=0}^{m,n} q_{m-i, n-j} s_{i,j} \right) x^m y^n \\ &= q(x, y) s(x, y); \end{aligned}$$

similarly

$$\sum P_{m,n}(N, p_{m,n})(s) x^m y^n = p(x, y) s(x, y).$$

Thus

$$\sum Q_{m,n}(N, q_{m,n})(s) x^m y^n = \sum k_{m,n} x^m y^n \sum P_{m,n}(N, p_{m,n})(s) x^m y^n$$

which implies that

$$Q_{m,n}(N, q_{m,n})(s) = \sum_{i,j=0}^{m,n} k_{m-i, n-j} P_{i,j}(N, p_{i,j})(s).$$

Hence,

$$(N, q_{m,n})(s) = \sum_{i,j=0}^{m,n} c_{m,n,i,j} (N, p_{i,j})(s), \quad (28)$$

where

$$c_{m,n,i,j} = k_{m-i, n-j} P_{i,j} / Q_{m,n}.$$

If $(N, p_{m,n}) \subseteq (N, q_{m,n})$, $(c_{m,n,i,j})$ is regular and so, by Theorem 2 (a), $\lim_{m+n \rightarrow \infty} c_{m,n,0,0} = 0$,

$$\text{i.e., } \lim_{m+n \rightarrow \infty} \frac{|k_{m,n}| |p_{0,0}|}{|q_{0,0}|} = 0,$$

which implies that $\lim_{m+n \rightarrow \infty} k_{m,n} = 0$.

Conversely, if $\lim_{m+n \rightarrow \infty} k_{m,n} = 0$, we can easily verify that $(c_{m,n,i,j})$ is regular. Consequently, using (28), it follows that $(N, p_{m,n}) \subseteq (N, q_{m,n})$. This completes the proof of the theorem.

Theorem 6, stated below, is an immediate consequence of Theorem 5.

Theorem 6. *If $(N, p_{m,n})$ and $(N, q_{m,n})$ are regular Nörlund methods, then they are equivalent if and only if $\lim_{m+n \rightarrow \infty} k_{m,n} = 0$ and $\lim_{m+n \rightarrow \infty} l_{m,n} = 0$.*

Remark. For the analogue of Theorem 6 in the classical case, see [5], Theorem III. Theorem 5, Theorem 6, in the case of regular Nörlund means for simple sequences, were established earlier by Natarajan (see[7], Theorem 3, Theorem 4).

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References

- [1] G. Bachman, Introduction to p -adic numbers and valuation theory, Academic Press, (1964).
- [2] G.H. Hardy, Divergent series, Oxford (1949).
- [3] Kojima, On the theory of double sequences, *Tôhoku Mathematical Journal*, 21 (1922), 3-14.
- [4] A.F. Monna, Sur le théorème de Banach-Steinhaus, *Indag. Math.* 25 (1963), 121-131.
- [5] C.N. Moore, On relationships between Nörlund means for double series, *Proc. Amer. Math. Soc.* 5 (1954), 957-963.
- [6] P.N. Natarajan, Criterion for regular matrices in non-archimedean fields, *J. Ramanujan Math. Soc.* 6 (1991), 185-195.
- [7] P.N. Natarajan, On Nörlund method of summability in non-archimedean fields, *J. Analysis* 2 (1994), 97-102.
- [8] G.M. Robison, Divergent double sequences and series, *Trans. Amer. Math. Soc.* 28 (1926), 50-73.
- [9] V.K. Srinivasan, On certain summation processes in the p -adic field, *Indag. Math.* 27 (1965), 319-325.

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