SOME MATRIX AND COMPACT OPERATORS OF THE ABSOLUTE FIBONACCI SERIES SPACES

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Abstract. In the present paper, we introduce the absolute Fibonacci space $|F_n|_k$, give some inclusion relations and investigate topological and algebraic structure such as BK-space, $\alpha$-, $\beta$-, $\gamma$- duals and Schauder basis. Further, we characterize certain matrix and compact operators on these spaces, also determine their norms and Hausdroff measures of noncompactness.

1. Introduction

Let $\omega$ be the set of all sequences of complex numbers. We write $c$, $\ell_\infty$, $c_s$, $b_s$ and $\ell_k$, $k \geq 1$, for the sequence space of all convergent, bounded sequences; for the spaces of all convergent, bounded, $k$-absolutely convergent series, respectively. Let $X$ and $Y$ be two subspaces of $\omega$ and $A = (a_{nv})$ be an arbitrary infinite matrix of complex numbers. If the series

$$A_n(x) = \sum_{v=0}^\infty a_{nv}x_v,$$

converges for all $n \in \mathbb{N} = \{0, 1, 2, \ldots\}$, then, by $A(x) = (A_n(x))$, we denote the $A$-transform of the sequence $x = (x_v)$. Also, we say that $A$ defines a matrix transformation from $X$ into $Y$, and denote it by $A \in (X, Y)$ or $A : X \to Y$ if $Ax = (A_n(x)) \in Y$ for every $x \in X$. The $\alpha$-, $\beta$-, $\gamma$- duals of $X$ and the domain of the matrix $A$ in $X$ are defined by

$$X^\alpha = \{\epsilon \in \omega : (\epsilon_n x_n) \in \ell \text{ for all } x \in X\},$$

$$X^\beta = \{\epsilon \in \omega : (\epsilon_n x_n) \in c_s \text{ for all } x \in X\},$$

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\[ X^\gamma = \{ \epsilon \in \omega : (\epsilon_n x_n) \in b_n \text{ for all } x \in X \} \]

and

\[ X_A = \{ x = (x_n) \in \omega : A(x) \in X \}, \]

respectively. Further, \( X \) is said to be a BK-space if it is a complete normed space with continuous coordinates \( p_n : X \to \mathbb{C} \) defined by \( p_n(x) = x_n \) for all \( n \in \mathbb{N} \). If there exists unique sequence of coefficients \( (x_k) \) such that, for each \( x \in X \),

\[ \left\| x - \sum_{k=0}^{m} x_k b_k \right\| \to 0, \quad m \to \infty, \]

then, the sequence \( (b_k) \) is called the Schauder basis (or briefly basis) for a normed sequence space \( X \), and in this case we write \( x = \sum_{k=0}^{\infty} x_k b_k \). For instance, the sequence \( (e^{(j)}) \) is the Schauder basis of the space \( \ell_k \), where \( e^{(j)} \) is the sequence whose only non-zero term is 1 in \( j \)th place for each \( j \in \mathbb{N} \).

Now take \( \sum x_v \) as an infinite series with \( n \)th partial sum \( s_n \) and let \( (u_n) \) be a sequence of positive terms. Then, the series \( \sum x_v \) is said to be summable \( |A,u_n|_k \), \( k \geq 1 \), if (see [32])

\[ \sum_{n=0}^{\infty} u_n^{k-1} |\Delta A_n(s)|^k < \infty, \]

where \( \Delta A_0(s) = A_n(s) - A_{n-1}(s), \quad A_{-1}(s) = 0. \)

Note that this method includes some well known methods. For example, if \( A \) is the matrix of weighted mean \( (\tilde{N}, p_n) \) (resp. \( u_n = P_n/p_n \)), then it reduces to the summability \( |\tilde{N}, p_n, u_n|_k \) [36] (the summability \( |\tilde{N}, p_n|_k \) [10]). Also if we take \( A \) as the matrix of Cesàro mean of order \( \alpha > -1 \) and \( u_n = n \), then we get summability \( |C, \alpha|_k \) in Flett’s notation [11].

A large literature has recently grown up, concerned with producing sequence spaces by means of matrix domain of a special limitation method and studying their algebraic, topological structure and matrix transformations (see [1–7, 15–18, 25]). Also, some series spaces have been derived and studied by absolute summability methods from a different point of view (see [9–14, 23–26, 28–34, 36]). The aim of this paper is to define the space \( |F_n|_k \) combining absolute summability and Fibonacci matrix given by Kara [15], investigate some inclusion relation, construct their \( \alpha- \), \( \beta- \), \( \gamma- \) duals, basis and characterize some matrix operators related to that space, and also determine their norms and Hausdorff measures of noncompactness.

Firstly, we mention some properties of Fibonacci numbers as follows: the sequence \( (f_n) \) of Fibonacci numbers is given by the relations

\[ f_0 = f_1 = 1 \text{ and } f_n = f_{n-1} + f_{n-2} \text{ for } n \geq 2 \]

that is, each term is equal to the sum of the previous two terms. The sequences of Fibonacci numbers have been important for artist, architects, physicists and mathematicians since the old. The ratio of Fibonacci numbers converges to the golden ratio which is one of the most interesting irrationals having an important role in number
theory, algorithms, network theory, etc. Also, Fibonacci numbers have the following properties [19]:

\[ \sum_{n=1}^{\infty} \frac{1}{f_n} \text{ converges,} \]

\[ f_{n-1}^2 + f_n f_{n-1} - f_n^2 = (-1)^{n+1}, \quad n \geq 1, \]

\[ \lim_{n \to \infty} \frac{f_{n+1}}{f_n} = \frac{1 + \sqrt{5}}{2} = 1.61803398875 \ldots. \]

Fibonacci matrix \( F = (\mathbf{\hat{f}}_{nv}) \) has recently been defined by Kara [15] as follows:

\[ \mathbf{\hat{f}}_{nv} = \begin{cases} -f_{n+1}, & v = n - 1, \\ \frac{f_n}{f_{n+1}}, & v = n, \\ 0, & v > n \text{ or } 0 \leq v < n - 1, \end{cases} \]

where \( f_n \) be the \( n \)th Fibonacci number for every \( n \in \mathbb{N} \). Note that if we take the Fibonacci matrix instead of \( A \), then \( |A, u_n|_k \) summability reduces to the absolute Fibonacci summability. On the other hand, since \((s_n)\) is a sequence of partial sum of the series \( \sum x_v \), we get

\[ A_n(s) = \sum_{v=0}^{n} \mathbf{\hat{f}}_{nv}s_v = \sum_{j=0}^{n} x_j \sum_{v=j}^{n} \mathbf{\hat{f}}_{nv} = x_n \mathbf{\hat{f}}_{nn} + \sum_{j=0}^{n-1} (\mathbf{\hat{f}}_{nn} + \mathbf{\hat{f}}_{n,n-1}) x_j \]

and so,

\[ \Delta A_n(s) = x_n \frac{f_n}{f_{n+1}} + x_{n-1} \left( \frac{(-1)^n}{f_n f_{n+1}} - \frac{f_{n+1}}{f_n} \right) + \sum_{j=0}^{n-2} (-1)^n \frac{f_{n-1} + f_{n+1}}{f_{n-1} f_n f_{n+1}} x_j \]

\[ = \sum_{j=0}^{n} \sigma_{nj} x_j, \]

where

\[ \sigma_{nj} = \begin{cases} \frac{f_n}{f_{n+1}}, & j = n, \\ (-1)^n \frac{f_n}{f_{n+1}}, & j = n - 1, \\ \frac{(-1)^n f_{n-1} + f_{n+1}}{f_{n-1} f_n f_{n+1}}, & 0 \leq j \leq n - 2, \\ 0, & j > n. \end{cases} \]

Now, we introduce the absolute Fibonacci space as follows:

\[ |F_{u|k} = \left\{ x \in \omega : \sum_{n=0}^{\infty} u_n^{k-1} \left| \sum_{j=0}^{n} \sigma_{nj} x_j \right|^k < \infty \right\}. \]

Also, it may be written that

\[ (E^{(k)} \circ T)_n(x) = u_n^{1/k^r} (T_n(x) - T_{n-1}(x)), \]
where

\[
t_{nv} = \begin{cases} 
  f_n, & v = n, \\
  f_{n+1}, & v > n,
\end{cases}
\]

\[
e_{nv}^{(k)} = \begin{cases} 
  u_n^{1/k^*}, & v = n, \\
  -u_n^{1/k^*}, & v = n - 1, \\
  0, & v \neq n, n - 1
\end{cases}
\]

and \( k^* \) is the conjugate of \( k \), i.e., \( 1/k + 1/k^* = 1 \) for \( k > 1 \), and \( 1/k^* = 0 \) for \( k = 1 \). With these matrices \( T = (t_{nv}) \) and \( E^{(k)} = (e_{nv}^{(k)}) \), according to the notation (1.1), it is obvious that \( |F_u|_k = (\ell_k)_{E^{(k)} \circ T} \). Further, since every triangle matrix has a unique inverse which also is a triangle [37], \( T \) and \( E^{(k)} \) have a unique inverse \( \tilde{T} = (\tilde{t}_{nv}) \) and \( \tilde{E}^{(k)} = (\tilde{e}_{nv}) \) given by

\[
\tilde{t}_{nv} = \begin{cases} 
  f_{n+1}, & v = n, \\
  f_n, & 0 \leq v \leq n - 1, \\
  f_{v}f_{v+1}, & v > n,
\end{cases}
\]

\[
\tilde{e}_{nv}^{(k)} = \begin{cases} 
  u_v^{-1/k^*}, & 0 \leq v \leq n, \\
  0, & v > n
\end{cases}
\]

respectively.

Before the main theorems, we point out some well known lemmas which are needed in the proofs of theorems.

**Lemma 1.1** ([35]). Let \( 1 < k < \infty \). Then, \( A \in (\ell_k, \ell) \) if and only if

\[
\|A\|_{(\ell_k, \ell)} = \sup_{N \in \mathfrak{F}} \left\{ \sum_{n=0}^{\infty} \left( \sum_{v=0}^{\infty} |a_{nv}| \right)^{k^*} \right\}^{1/k^*}
\]

where \( \mathfrak{F} \) denotes the collection of all finite subsets of \( \mathbb{N} \).

Lemma 1.1 exposes a rather difficult condition to apply in applications. So the following lemma is more useful in many cases, which gives equivalent norm.

**Lemma 1.2** ([29]). Let \( 1 < k < \infty \). Then, \( A \in (\ell_k, \ell) \) if and only if

\[
\|A\|_{(\ell_k, \ell)}' = \left\{ \sum_{v=0}^{\infty} \left( \sum_{n=0}^{\infty} |a_{nv}| \right)^{k^*} \right\}^{1/k^*} < \infty.
\]

Moreover, since

\[
\|A\|_{(\ell_k, \ell)} \leq \|A\|_{(\ell_k, \ell)}' \leq 4 \|A\|_{(\ell_k, \ell)},
\]

there exists \( 1 \leq \xi \leq 4 \) such that \( \|A\|_{(\ell_k, \ell)}' = \xi \|A\|_{(\ell_k, \ell)} \).
Lemma 1.3 ([20]). Let $1 \leq k < \infty$. Then, $A \in (\ell, \ell_k)$ if and only if

$$\|A\|_{(\ell, \ell_k)} = \sup_{n, v} \left\{ \sum_{n=0}^{\infty} |a_{nv}|^k \right\}^{\frac{1}{k}}.$$

Lemma 1.4 ([35]).

(a) $A \in (\ell, c) \iff (i) \lim_n a_{nv}$ exists for $v \geq 0$, (ii) $\sup_{n, v} |a_{nv}| < \infty$;
(b) $A \in (\ell, \ell_\infty) \iff (ii)$ holds;
(c) If $1 < k < \infty$, then, $A \in (\ell_k, c) \iff (i)$ holds; (iii) $\sup_n \sum_{v=0}^{\infty} |a_{nv}|^k < \infty$;
(d) If $1 < k < \infty$, then, $A \in (\ell_k, \ell_\infty) \iff (iii)$ holds.

2. The Hausdorff Measure of Noncompactness

If $S$ and $H$ are subsets of a metric space $(X, d)$ and, for every $h \in H$, there exists an $s \in S$ such that $d(h, s) < \varepsilon$ then, $S$ is called an $\varepsilon$-net of $H$; if $S$ is finite, then the $\varepsilon$-net $S$ of $H$ is called a finite $\varepsilon$-net of $H$. Let $X$ and $Y$ be Banach spaces. A linear operator $L : X \to Y$ is called compact if its domain is all of $X$ and, for every bounded sequence $(x_n)$ in $X$, the sequence $(L(x_n))$ has a convergent subsequence in $Y$. We denote the class of such operators by $\mathcal{C}(X, Y)$. If $Q$ is a bounded subset of the metric space $X$, then the Hausdorff measure of noncompactness of $Q$ is defined by

$$\chi(Q) = \inf \{ \varepsilon > 0 : Q \text{ has a finite } \varepsilon - \text{net in } X \},$$

and $\chi$ is called the Hausdorff measure of noncompactness.

The following lemma is very important to calculate the Hausdorff measure of noncompactness of a bounded subset of the space $\ell_k$.

Lemma 2.1 ([27]). Let $Q$ be a bounded subset of the normed space $X$ where $X = \ell_k$ for $1 \leq k < \infty$ or $X = c_0$. If $P_n : X \to X$ is the operator defined by $P_n(x) = (x_0, x_1, \ldots, x_n, 0, 0, \ldots)$ for all $x \in X$, then

$$\chi(Q) = \lim_{r \to \infty} \left( \sup_{x \in Q} \| (I - P_r)(x) \| \right).$$

Let $X$ and $Y$ be Banach spaces and $\chi_1$ and $\chi_2$ be Hausdorff measures on $X$ and $Y$, the linear operator $L : X \to Y$ is said to be $(\chi_1, \chi_2)$- bounded if $L(Q)$ is a bounded subset of $Y$ and there exists a positive constant $M$ such that $\chi_2(L(Q)) \leq M \chi_1(L(Q))$ for every bounded subset $Q$ of $X$. If an operator $L$ is $(\chi_1, \chi_2)$- bounded, then the number

$$\|L\|_{(\chi_1, \chi_2)} = \inf \{ M > 0 : \chi_2(L(Q)) \leq M \chi_1(L(Q)) \text{ for all bounded set } Q \subset X \}$$

is called the $(\chi_1, \chi_2)$-measure noncompactness of $L$. In particular, if $\chi_1 = \chi_2 = \chi$ then we write $\|L\|_{(\chi, \chi)} = \|L\|_{\chi}$.}
Lemma 2.2 ([22]). Let $X$ and $Y$ be Banach spaces and $L \in B(X,Y)$. Also $S_x = \{x \in X : \|x\| \leq 1\}$ be the unit sphere in $X$. Then,

$$\|L\|_\chi = \chi(L(S_x))$$

and

$$L \in \mathcal{C}(X,Y) \iff \|L\|_\chi = 0.$$

Lemma 2.3 ([21]). Let $X$ be a normed sequence space, $T = (t_{nv})$ be an infinite triangle matrix, $\chi_T$ and $\chi$ denote the Hausdorff measures of noncompactness on $M_{X_T}$ and $M_X$, the collections of all bounded sets in $X_T$ and $X$, respectively. Then, $\chi_T(Q) = \chi(T(Q))$ for all $Q \in M_{X_T}$.

3. Absolute Fibonacci Space $|F_u|_k$

In this section, we investigate some inclusion relations, topological and algebraic structures of the space $|F_u|_k$. Also we characterize some classes of compact matrix operators on that space and compute their norms and Hausdorff measure of noncompactness.

Firstly, since $|F_u|_k$ is generated from $\ell_k$, to explain a relation between the spaces $\ell_k$ and $|F_u|_k$, we begin with the following theorem.

Theorem 3.1. Let $u = (u_n) \in \ell_\infty$ and $1 \leq k < \infty$. Then, $\ell_k \subset |F_u|_k$.

Proof. To prove the inclusion $\ell_k \subset |F_u|_k$, it is sufficient to show that

$$\|x\|_{|F_u|_k} \leq O(1) \|x\|_{\ell_k},$$

for all $x \in \ell_k$. The proof is clear for the case $k = 1$, and so it is omitted. Let $k > 1$. Then, since the series $\sum n \frac{1}{f_n}$ is convergent and $\left(\frac{1}{f_n}\right)$ is decreasing sequence, it follows from Abel’s Theorem, $\frac{1}{f_n} \to 0$ as $n \to \infty$, $\sum n \sigma_{nv} = O(1)$ and $\sum \sigma_{nv} = O(1)$. Now applying Hölder’s inequality, we get

$$\|x\|_{|F_u|_k} = \left\{ \sum_{n=0}^\infty u_n^{k-1} \left( \sum_{v=0}^n |\sigma_{nv}x_v| \right)^k \right\}^{1/k} \leq \left\{ \sum_{n=0}^\infty u_n^{k-1} \left( \sum_{v=0}^n |x_v|^k \right)^k \left( \sum_{v=0}^n |\sigma_{nv}| \right)^{k/k^*} \right\}^{1/k} = O(1) \left\{ \sum_{v=0}^\infty |x_v|^k \sum_{n=v}^\infty |\sigma_{nv}| \right\}^{1/k} \leq O(1) \left\{ \sum_{v=0}^\infty |x_v|^k \right\}^{1/k} = O(1) \|x\|_{\ell_k},$$

which completes the proof. \(\square\)
**Theorem 3.2.** Let $1 \leq k \leq q < \infty$. If there is a constant $M > 0$ such that $u_n \leq M$ for all $n \in \mathbb{N}$, then $|F_u|_k \subset |F_u|_q$.

*Proof.* Take $x \in |F_u|_k$. Since $\ell_k \subset \ell_q$, then \( \left( u_n^{1/k} \sum_{j=0}^{n} \sigma_n x_j \right) \in \ell_q \) and also, since $u_n \leq M$ for all $n \in \mathbb{N}$,

\[
M^{q^*-\frac{2}{q}^*} \left|\frac{1}{n} \sum_{j=0}^{n} \sigma_n x_j \right|^q \leq \left| u_n^{1/k} \sum_{j=0}^{n} \sigma_n x_j \right|^q \text{,}
\]

where $k^*$ and $q^*$ are the conjugate of exponent of $k$ and $q$, respectively. So this gives that $x \in |F_u|_q$, which completes the proof. \(\square\)

**Theorem 3.3.** Let $1 \leq k < \infty$. Then, $|F_u|_k$ is BK-space with respect to the norm

\[
\|x\|_{|F_u|_k} = \|E^{(k)} \circ T(x)\|_{\ell_k^*} \text{.}
\]

Also, the sequence $b^{(j)} = (b^{(j)}_n)$ is a Schauder basis for the space $|F_u|_k$, where

\[
b^{(j)}_n = \begin{cases} 
  u_n^{-1/k} \frac{f_{n+1}}{f_n} + u_n^{-1/k} \sum_{r=j}^{n-1} \frac{f_{r+1}^2 - f_r^2}{f_r f_{r+1}}, & 0 \leq j \leq n - 1 \\
  u_n^{-1/k} \frac{f_{n+1}}{f_n}, & j = n \\
  0, & j > n.
\end{cases}
\]

*Proof.* We note that $\ell_k$ is a BK-space for $1 \leq k < \infty$. Further, since $E^{(k)} \circ T$ is a triangle matrix, it follows from Theorem 4.3.2 of [37], $|F_u|_k = (\ell_k)_{E^{(k)} \circ T}$ is a BK-space. Since the sequence $(e^{(j)})$ is the Schauder basis of the space $\ell_k$, it can be written from Theorem 2.3 in [14] that $b^{(j)} = (T_n(E^{(k)}(e^{(j)})))$ is a Schauder basis of the space $|F_u|_k$. \(\square\)

**Theorem 3.4.** Let $1 \leq k < \infty$. Then, the space $|F_u|_k$ is isomorphic to the space $\ell_k$ that is, $|F_u|_k \cong \ell_k$.

*Proof.* To prove the theorem, we should show that there exists a linear bijection between the spaces $|F_u|_k$ and $\ell_k$ where $1 \leq k < \infty$. Let consider the transformations $T : |F_u|_k \to (\ell_k)_{E^{(k)}}, E^{(k)} : (\ell_k)_{E^{(k)}} \to \ell_k$ given in (1.3) and (1.4). Since the matrices corresponding these transformations are triangles, it can be easily seen that $T$ and $E^{(k)}$ are linear bijections. So, the composite function $E^{(k)} \circ T$ is a linear bijective operator. Furthermore,

\[
\|x\|_{|F_u|_k} = \|E^{(k)} \circ T(x)\|_{\ell_k^*} \text{,}
\]

i.e., it preserves the norm. So the proof is completed. \(\square\)

In the following theorems, for the simplicity of presentation we take

\[
\xi_{v r} = \left( \frac{f_{v+1}}{f_v} + \left( \frac{f_{v+1}^2 - f_v^2}{f_v} \right) \sum_{j=r}^{v-1} \frac{1}{f_j f_{j+1}} \right)
\]
and define

\[ D_1 = \left\{ \epsilon \in \omega : \sum_{v=r+1}^{\infty} \xi_{vr} \epsilon_v \text{ exists for all } r \right\}, \]

\[ D_2 = \left\{ \epsilon \in \omega : \sup_m \left( \frac{1}{u_m} \epsilon_m \frac{f_{m+1}}{f_m} \right)^{k^*} + \sum_{r=0}^{m-1} \frac{1}{u_r} \epsilon_r \frac{f_{r+1}}{f_r} + \sum_{v=r+1}^{m} \xi_{vr} \epsilon_v \right) < \infty \}, \]

\[ D_3 = \left\{ \epsilon \in \omega : \sup_{m,r} \left( \epsilon_m \frac{f_{m+1}}{f_m} + \epsilon_r \frac{f_{r+1}}{f_r} + \sum_{v=r+1}^{m} \xi_{vr} \epsilon_v \right) < \infty \}, \]

\[ D_4 = \left\{ \epsilon \in \omega : \sum_{r=0}^{m} \frac{1}{u_r} \left( \sum_{v=r+1}^{\infty} |\xi_{vr} \epsilon_v| + |\epsilon_r \frac{f_{r+1}}{f_r}| \right)^{k^*} < \infty \}, \]

\[ D_5 = \left\{ \epsilon \in \omega : \sup_r \left( \sum_{v=r+1}^{\infty} |\xi_{vr} \epsilon_v| + |\epsilon_r \frac{f_{r+1}}{f_r}| \right) < \infty \}. \]

**Theorem 3.5.** Let 1 < k < \infty and u = (u_n) be a sequence of positive numbers. Then,

(i) \(|F_u|^{\alpha} = D_5, \{|F_u|^{\alpha} = D_4; \]

(ii) \(|F_u|^{\beta} = D_1 \cup D_3, \{|F_u|^{\beta} = D_1 \cap D_2; \]

(iii) \(|F_u|^{\gamma} = D_3, \{|F_u|^{\gamma} = D_2. \]

**Proof.** (ii) Let’s recall that \( \epsilon \in \{|F_u|^{\beta} \) if and only if \( \epsilon x = (\epsilon_n x_n) \in c_s \) for all \( x \in |F_u|_k. \)

By (1.3) and (1.4), it can be seen immediately that

\[ \sum_{v=0}^{m} \epsilon_v x_v = \epsilon_0 x_0 + \sum_{v=1}^{m} \epsilon_v \left( \frac{f_{v+1}}{f_v} y_v + (f_{v+1} - f_v^2) \sum_{j=0}^{v-1} \frac{y_j}{f_j f_{j+1}} \right) \]

\[ = \sum_{r=0}^{m} u_r^{-1/k^*} \sum_{v=r}^{m} \epsilon_v \frac{f_{v+1}}{f_v} z_r + \sum_{r=0}^{m-1} \left( \sum_{v=r+1}^{m} \epsilon_v (f_{v+1}^2 - f_v^2) \sum_{j=r}^{v-1} \frac{1}{f_j f_{j+1}} \right) u_r^{-1/k^*} z_r \]

\[ = u_m^{-1/k^*} \sum_{r=0}^{m} \epsilon_m \frac{f_{m+1}}{f_m} z_m + \sum_{r=0}^{m-1} u_r^{-1/k^*} \left( \epsilon_r \frac{f_{r+1}}{f_r} + \sum_{v=r+1}^{m} \epsilon_v \xi_{vr} \right) z_r \]

\[ = \sum_{r=0}^{m} h_{mr} z_r \quad (y = T(x), z = E^{(k)}(y)) \]

where \( H = (h_{mr}) \) is defined by

\[
    h_{mr} = \begin{cases} 
        u_r^{-1/k^*} \left( \epsilon_r \frac{f_{r+1}}{f_r} + \sum_{v=r+1}^{m} \epsilon_v \xi_{vr} \right), & 0 \leq r \leq m - 1, \\
        u_m^{-1/k^*} \frac{f_{m+1}}{f_m} \epsilon_m, & r = m, \\
        0, & r > m. 
    \end{cases}
\]

Therefore, \( \epsilon \in \{|F_u|^{\beta} \) if and only if \( H \in (\ell_k, c) \). Applying Lemma 1.4 to the matrix \( H \), we get \(|F_u|^{\beta} = D_1 \cap D_2, \) which completes the proof.

The proofs of other parts can similarly be proved, so we omit. \( \square \)
Theorem 3.6. Let $1 \leq k < \infty$, $A = (a_{nv})$ be an infinite matrix of complex numbers for each $n, v \in \mathbb{N}$ and define the matrix $B^{(n)} = \left( b_{nm}^{(n)} \right)$ by

$$b_{nm}^{(n)} = \begin{cases} a_{nr} \frac{f_{r+1}}{f_r} + \sum_{v=r+1}^{m} a_{nv} \xi_{vr}, & 0 \leq r \leq m - 1, \\ \frac{f_{m+1}}{f_m} a_{nm}, & r = m, \\ 0, & r > m. \end{cases}$$

Further, let $\bar{B} = (\bar{b}_{nv})$ be a matrix given by $\bar{b}_{nv} = \lim_{m} b_{mv}^{(n)}$ and $\tilde{B} = E^{(k)} \circ T \circ \bar{B}$. Then, $A \in (|F_u|, |F_u|_{k})$ if and only if

$$\sum_{v=r+1}^{\infty} \xi_{vr} a_{nv} \text{ exists for all } r \quad (3.1)$$

$$\sup_{m,r} \left\{ \left| a_{nm} \frac{f_{m+1}}{f_m} a_{nr} \frac{f_{r+1}}{f_r} + \sum_{v=r+1}^{m} \xi_{vr} a_{nv} \right| \right\} < \infty, \quad (3.2)$$

$$\sup_{r} \sum_{n=0}^{\infty} \frac{1}{u_r} \left| \bar{b}_{nr} \right|^k < \infty, \quad (3.3)$$

If $A \in (|F_u|, |F_u|_{k})$, then $A$ is a bounded linear operator,

$$\|A\|_{(|F_u|,|F_u|_{k})} = \|\tilde{B}\|_{(\ell, l_k)}$$

and

$$\|A\|_{\chi} = \lim_{v \to \infty} \left\{ \sup_{r} \sum_{n=v+1}^{\infty} \frac{1}{u_r} \left| \bar{b}_{nr} \right|^k \right\}^{\frac{1}{k}}.$$ 

Proof. $A \in (|F_u|, |F_u|_{k})$ if and only if $(a_{nv})_{v=0}^{\infty} \in \{|F_u|\}^{\beta}$ and $A(x) \in |F_u|_{k}$ for all $x \in |F_u|$. Now, it can be easily seen from Theorem 3.5, $(a_{nv})_{v=0}^{\infty} \in \{|F_u|\}^{\beta}$ if and only if (3.1) and (3.2) hold. On the other hand, if a matrix $R = (r_{nv}) \in (\ell, c)$, then the series $R_n(x) = \sum_{v=0}^{\infty} r_{nv} x_v$ converges uniformly in $n$, because, the remaining term of the series tends to zero uniformly in $n$, since

$$\left| \sum_{v=m}^{\infty} r_{nv} x_v \right| \leq \sup_{v} |r_{nv}| \sum_{v=m}^{\infty} |x_v| \to 0, \quad m \to \infty.$$ 

So we obtain

$$\lim_{n} R_n (x) = \sum_{v=0}^{\infty} \lim_{n} r_{nv} x_v. \quad (3.4)$$

Using (1.3), (1.4) and (3.4) it can be written that

$$A_n(x) = \lim_{m} \sum_{k=0}^{m} a_{nk} x_k = \lim_{m} \sum_{r=0}^{m} b_{mr}^{(n)} z_r = \sum_{r=0}^{\infty} \bar{b}_{nr} z_r.$$
Besides, according to Theorem 3.4, since $|F_{u_k}| \cong \ell_k$ for all $1 \leq k < \infty$, it follows that $A(x) \in |F_{u_k}|$ for all $x \in |F_u|$ if and only if $\tilde{B} \in (\ell, |F_{u_k}|)$, or equivalently, since $|F_{u_k}| = (\ell_k)_{E(k) \circ T}$, $\tilde{B} \in (\ell, \ell_k)$. Also, it is clear that the terms of matrix $\tilde{B}$ can be expressed as

$$\hat{b}_{nr} = \sum_{v=0}^{n} t_{nv} b_{v r} = \frac{f_n}{f_{n+1}} b_{nr} + \sum_{v=0}^{n-1} \frac{f_n^2 - f_{n+1}^2}{f_{n+1}} b_{v r},$$

$$\tilde{b}_{nr} = u_r^{1/k} (\hat{b}_{nr} - \hat{b}_{n-1,r}), \quad n \geq 1 \text{ and } \tilde{b}_{0r} = b_{0r}.$$

Hence, applying Lemma 1.3 to the matrix $\tilde{B}$, we have (3.3), which completes the first part of the proof.

Also, if $A \in (|F_u|, |F_{u_k}|)$, then, since the spaces $|F_{u_k}|$ and $|F_u|$ are $BK$-spaces, it is a bounded operator. In order to determine the operator norm of $A$, consider the isomorphisms $T : |F_{u_k}| \to (\ell_k)_{E(k)}$, $E(k) : (\ell_k)_{E(k)} \to \ell_k$ defined as in Theorem 3.4. Then, it is easy to see that $A = \tilde{T} \circ \tilde{E}(k) \circ \tilde{B} \circ E(1) \circ T$ and so,

$$\|A\|_{(|F_u|, |F_{u_k}|)} = \sup_{x \neq 0} \frac{\|A(x)\|_{|F_{u_k}|}}{\|x\|_{|F_u|}} = \frac{\|\tilde{T} \circ \tilde{E}(k) \circ \tilde{B} \circ E(1) \circ T(x)\|_{|F_{u_k}|}}{\|x\|_{|F_u|}} = \sup_{z \neq 0} \frac{\|\tilde{B}(z)\|_{\ell_k}}{\|z\|_{\ell_k}} = \|\tilde{B}\|_{(\ell, \ell_k)} (z = E(1) \circ T(x)).$$

Finally, assume that $Q$ is a unique ball in $|F_u|$. Since $E(k) \circ T \circ AQ = \tilde{B} \circ E(1) \circ TQ$, we get that

$$\|A\|_\chi = \chi(AQ) = \chi \left( E(k) \circ T \circ AQ \right) = \chi \left( \tilde{B} \circ E(1) \circ TQ \right)$$

$$= \lim_{v \to \infty} \left( \sup_{z \in E(1)(T(Q))} \| (I - P_z) (\tilde{B}(z)) \| \right)$$

$$= \lim_{v \to \infty} \left\{ \sup_r \left( \sum_{n=v+1}^{\infty} \frac{1}{u_r} |\tilde{b}_{nr}| \right)^k \right\}^{\frac{1}{k}}.$$ 

This completes the proof. \hfill \Box

By Theorem 3.6 and Lemma 2.2, the compact operators in this class are characterized as follows.

**Corollary 3.1.** Under the hypothesis of Theorem 3.6

$$A \in (|F_u|, |F_{u_k}|) \text{ is compact if and only if } \lim_{v \to \infty} \left\{ \sup_r \left( \sum_{n=v+1}^{\infty} \frac{1}{u_r} |\tilde{b}_{nr}| \right)^k \right\}^{\frac{1}{k}} = 0.$$ 

**Theorem 3.7.** Let $1 < k < \infty$, $A = (a_{nv})$ be an infinite matrix of complex numbers for all $n, v \in \mathbb{N}$ and $B^{(n)} = (b^{(n)}_{mv})$ be as in Theorem 3.6. Besides, define $H = (h_{nv})$
by $\tilde{h}_{nv} = \lim_m u^{-1/k^*}_{nr} b^{(n)}_{nr}$ and $H = E^{(1)} \circ T \circ \tilde{H}$. Then, $A \in (|F_u|, |F_u|)$ if and only if

$$\sum_{v=r+1}^{\infty} \xi_{nr}a_{nr} \text{ exist for all } r,$$

(3.5)

$$\sup_m \left\{ \frac{1}{u_m} \left| a_{nm} f_{m+1}^{k^*} + \sum_{r=0}^{m-1} \frac{1}{u_r} \left| a_{nr} f_{r+1}^{k^*} + \sum_{v=r+1}^{m} \xi_{v}a_{nv} \right|^{k^*} \right\} < \infty,$$

(3.6)

$$\sum_{r=0}^{\infty} \left( \sum_{n=0}^{\infty} |\tilde{h}_{nr}| \right)^{k^*} < \infty.$$

(3.7)

Moreover, if $A \in (|F_u|, |F_u|)$, then $A$ is a bounded linear operator,

$$\| A \|_{(|F_u|, |F_u|)} = \| \tilde{H} \|_{(\ell_k, \ell)}$$

and

$$\| A \|_{\chi} = \frac{1}{\xi} \lim_{v \to \infty} \left\{ \sum_{r=0}^{\infty} \left( \sum_{n=v+1}^{\infty} |\tilde{h}_{nr}| \right)^{\frac{k^*}{\xi}} \right\}^{\frac{1}{k^*}},$$

where $1 \leq \xi \leq 4$.

Proof. $A \in (|F_u|, |F_u|)$ if and only if $A_n = (a_{nm})_{v=0}^{\infty} \in \{ [F_u]_{k} \}^3$ and $A(x) \in |F_u|$ where $x \in |F_u|_k$. By Theorem 3.5, it can be easily seen that $A_n \in \{ [F_u]_{k} \}^3$ if and only if (3.5) and (3.6) hold. Also, if any matrix $R = (r_{nm}) \in (\ell_k, c)$, then the series $R_n(x) = \sum_{v=0}^{\infty} r_{nv}x_v$ converges uniformly in $n$. Because, the remaining term of the series tends to zero uniformly in $n$, since

$$\left| \sum_{v=m}^{\infty} r_{nv}x_v \right| \leq \left( \sum_{v=m}^{\infty} |r_{nv}|^{k^*} \right)^{\frac{1}{k^*}} \left( \sum_{v=m}^{\infty} |x_v|^k \right)^{\frac{1}{k}} \to 0, \quad m \to \infty$$

and so, it can be written that

$$\lim_{n} R_n(x) = \sum_{v=0}^{\infty} \lim_{n} r_{nv}x_v.$$

Then, using (3.8), with a few calculations, we get

$$A_n(x) = \lim_{m} m \sum_{k=0}^{m} a_{nk}x_k = \lim_{m} m \sum_{r=0}^{m} u^{-1/k^*}_{r} b^{(n)}_{mr}z_r = \sum_{r=0}^{\infty} \tilde{h}_{nr}z_r.$$
Additionally, as Theorem 3.4, it can be written that 
\[ A = \tilde{T} \circ \tilde{E}^{(1)} \circ \tilde{H} \circ E^{(k)} \circ T \]
and so,
\[ \|A\|_{\mathcal{C}(\vert F_u \vert, \vert F_u \vert)} = \sup_{x \neq 0} \frac{\|A(x)\|_{\mathcal{O}(\vert F_u \vert)}}{\|x\|_{\mathcal{O}(\vert F_u \vert)}} = \sup_{x \neq 0} \frac{\|\tilde{H} \circ E^{(k)} \circ T(x)\|_{\ell_k}}{\|E^{(k)} \circ T(x)\|_{\ell_k}} \]
\[ = \sup_{z \neq 0} \frac{\|\tilde{H}(z)\|_{\ell_k}}{\|z\|_{\ell_k}} = \|\tilde{H}\|_{(\ell_k, \ell_k)}. \]

Finally, let \( Q = S_{\vert F_u \vert} \). Since \( E^{(1)} \circ T \circ AQ = \tilde{H} \circ E^{(k)} \circ TQ \), it follows by Lemma 2.1, Lemma 2.3 and Lemma 1.2 that
\[ \|A\|_{\chi} = \chi(AQ) = \chi(E^{(1)} \circ T \circ AQ) = \chi(\tilde{H} \circ E^{(k)} \circ TQ) \]
\[ = \lim_{v \to \infty} \left( \sup_{z \in E^{(k)}(T(Q))} \left\| (I - P_v)(\tilde{H}(z)) \right\|_{\ell_k} \right) \]
\[ = \frac{1}{\xi} \lim_{v \to \infty} \left\{ \sum_{r=0}^{\infty} \left( \sum_{n=v+1}^{\infty} \left| \tilde{h}_{nr} \right| \right)^{\frac{1}{p}} \right\}, \]
which completes the proof. \( \square \)

Also, the compact operators can immediately be characterized by Lemma 2.2 and Theorem 3.7 as follows.

**Corollary 3.2.** Under the conditions of Theorem 3.7
\[ A \in \mathcal{C}(\vert F_u \vert, \vert F_u \vert) \Leftrightarrow \frac{1}{\xi} \lim_{v \to \infty} \left\{ \sum_{r=0}^{\infty} \left( \sum_{n=v+1}^{\infty} \left| \tilde{h}_{nr} \right| \right)^{\frac{1}{p}} \right\} = 0. \]

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