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ON SOME INEQUALITIES FOR QUASI-MONOTONE SEQUENCES

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0. Let $p \neq 0$ be a real constant. The operator L_p will be defined in the following way (see [**1**]):

$$L_p(a_n) = a_{n+1} - pa_n \quad (n \in N).$$

For a sequence $a = (a_n)$ we shall say that it is p-monotone or that it belongs to the class K_p if the inequality

$$L_p(a_n) \geq 0$$

is valid for all $n \in N$.

The following theorem is given in [**1**];

THEOREM A. *Let for a given sequence $a = (a_n)$ the sequaence $A = (A_n)$ be defined by*

$$A_n = \frac{p_1 a_1 + \cdots + p_n a_n}{p_1 + \cdots + p_n}.$$

(i) *If we have $p = q$ then the implication*

$$a \in K_n \Rightarrow A \in K_q \tag{1}$$

holds true for every sequence of the class K_p and for arbitrary positive weights $p = (p_n)$ if and only if $p = q = 1$.

(ii) *If p and q satisfy one of the conditions*

$$p > q > 1; \; 0 < p < q < 1; \quad or \quad p < q < 0,$$

then implication (1) *holds true for an arbitrary sequence of the class K_p if and only if the sequence $p = (p_n)$ of positive weights is given by*

$$p_n = p_1 \frac{qn - 1 - q^{n-2}}{p^{n-1} - q^{n-2}} \prod_{k=1}^{n-1} \frac{p^k - q^{k-1}}{p^k - q^k} \quad (n = 2, 3, \dots)$$

where the weight p_1 is an arbitrary given positive number.

1. In this paper we shall shown that some inequalities for monotone sequences are also valid for p-monotone sequences, i.e. we shall give the necessary and sufficien conditions for the validity of these inequalities.

First, we shall notice that the following identity follows, from the well-known Abel identity:

$$\sum_{i=1}^{n} w_i a_i = a_1 \sum_{i=1}^{n} p^{i-1} w_i \sum_{k=2}^{n} \Big(\sum_{i=k}^{n} p^{i-k} w_i \Big) L_p(a_{k-1}). \tag{2}$$

Using (2), we can easily obtain the following theorem:

THEOREM 1. *Let $w = (w_n)$ be an arbitrary real sequence.*

(a) *Inequality*

$$\sum_{i=1}^{n} w_i a_i \geq 0 \tag{3}$$

holds for every sequence a from K_p if and only if

$$\sum_{i=1}^{n} p^{i-1} w_i = 0$$

and

$$\sum_{i=k}^{n} p^{i-k} w_i \geq 0 \quad (k = 2, \dots, n).$$

(b) *Inequality* (3) *holds for every sequence a from K_p such that $a_1 \geq 0$ if and only if*

$$\sum_{i=k}^{n} p^{i-k} w_i \geq 0 \quad (k = 1, \dots, n).$$

2. Let $a \in K_p$, $b \in K_q$ be real sequences, and let $x_{ij} (i = 1, \dots, n; j = 1, \dots, m)$ be real numbers. Then necessary and suficient conditions for the numbers x_{ij}, such that the inequality

$$F(a,b) = \sum_{i=1}^{n} \sum_{j=1}^{m} x_{ij} a_i b_j \geq 0 \tag{4}$$

holds: 1° for every p-monotone sequence a and for every q-monotone sequence b, or 2° for every p-monotone sequence a and q-monotone sequence b such that $a_1 \geq 0$ and $b_1 \geq 0$, are contained in the following theorem:

THEOREM 2. (a) *With the condition* 1°, $F(a,b) \geq 0$ *if and only if*

$$\begin{gathered} X_{1,s} = 0, \ (s = 1, \dots, m), \quad X_{r,1} = 0 \ (r = 2, \dots, n) \\ X_{r,s} \geq 0 \ (r = 2, \dots, n; \ s = 2, \dots, m), \end{gathered} \tag{5}$$

where

$$X_{r,s} = \sum_{i=r}^{n}\sum_{j=s}^{m} p^{i-r} q^{j-s} x_{ij}.$$

(b) *With the condition* 2°, $F(a,b) \geq 0$, *if and only if*

$$X_{r,s} \geq 0 \ \ (r = 1, \dots, n; \ \ s = 1, \dots, m).$$

Proof. (a) (i) Let $a_i = 0$ $(i = 1, \dots, r-1)$ $a_i = p^{i-r}(i = r, \dots, n)$, and let $b_j = q^{j-1}(j = 1, \dots, m)$ or $b_j = -q^{j-1}(j = 1, \dots, m)$. Then from (4), we get the condition $X_{r,1} = 0$. By analogy, we get $X_{1,s} = 0$. Now, let

$$\begin{aligned} a_i =& 0\,(i = 1, \dots,\ r-1) \quad a_i = p^{i-r}(i = r, \dots, n),\\ b_j =& 0\,(j = 1, \dots, s-1) \quad b_j = p^{j-s}(j = s, \dots, m). \end{aligned}$$

Then, from (4), we get $X_{r,s} \geq 0$. So condition (5) is necessary.

(ii) Let be $s_j = \sum\limits_{i=1}^{n} x_{ij} a_i$. Then

$$f(a,b) = \sum_{j=1}^{m} s_j b_j = b_1 \sum_{j=1}^{m} q^{j-1} s_j + \sum_{s=2}^{m}\left(\sum_{j=s}^{m} q^{j-s} s_j\right) L_q(b_{s-1}).$$

Now, we write $x_i = \sum\limits_{j=s}^{m} q^{j-s} x_{ij}$. Then

$$\begin{aligned} \sum_{j=s}^{m} q^{j-s} s_j =& \sum_{i=1}^{n}\left(\sum_{j=s}^{m} q^{j-s} x_{ij}\right) a_i = \sum_{i=1}^{n} x_i a_i\\ =& a_1 \sum_{i=1}^{n} p^{i-1} x_i + \sum_{r=2}^{n}\left(\sum_{i=r}^{n} p^{i-r} x_i\right) L_p(a_{r-1})\\ =& a_1 X_{1,s} + \sum_{r=2}^{n} X_{r,s} L_p(a_{r-1}). \end{aligned}$$

For $s = 1$, we have

$$\sum_{j=1}^{m} q^{j-1} s_j = a_1 X_{1,1} + \sum_{r=2}^{n} X_{r,1} L_p(a_{r-1}).$$

So,

$$\begin{aligned} F(a,b) = a_1 b_1 X_{1,1} &+ b_1 \sum_{r=2}^{n} X_{r,1} L_p(a_{r-1}) + a_1 \sum_{s=2}^{m} X_{1,s} L_q(b_{s-1})\\ &+ \sum_{r=2}^{n}\sum_{s=2}^{m} X_{r,s} L_p(a_{r-1}) L_q(b_{s-1}). \end{aligned}$$

Based on (5), it is evident that (4) holds.

Analogously we can prove (b).

REMARK. *For $p = q = 1$, we have the result from* [**2**].

Analogously to the previous proof (see also [**3**]), we can prove the following theorem:

THEOREM 3. *Let $a_j = (a_{j1}, \dots, a_{jn})$ $(j = 1, \dots, m)$ be real sequences and let $x_{j_1} \dots j_m (j_k = 1, \dots, n_k,\ k = 1, \dots, m)$ be real numbers. Then necessary and sufficient conditions for the numbers $x_{j_1} \dots j_m$, for the inequality*

$$\sum_{j_1=1}^{n_1} \cdots \sum_{j_1=1}^{n_m} x_{j_1} \dots j_m a_{1j_1} \cdots a_{mj_m} \geq 0$$

to hold for every p_j-monotone sequence a_j such that $a_{j1} \geq 0$ $(j = 1, \dots, m)$ are

$$\sum_{j_1=s_1}^{n_1} \cdots \sum_{j_m=s_m}^{n_m} p_1^{j_1-s_1} \cdots p_m^{j_m-s_m} x_{j_1} \dots j_m \geq 0$$

for $j_k = 1, \dots, n_k,\ k = 1, \dots, m$.

REMARK. *For $p_1 = \cdots = p_m = 1$, we have the result from* [**3**].

3. Now, we shall give a generalization of Theorem A.

Let us consider a triangular matrix of real numbers $(p_{n,i})$ (where $= 0, 1, \dots, n$; $n = 0, 1, \dots$). Let us define the sequence (σ_n), for a given sequence (a_n) by

$$\sigma_n = \sum_{j=0}^{n} p_{n,n-j} a_j. \tag{5}$$

Then the following theorem holds:

THEOREM 4. *A necessary and sufficient condition for the implication*

$$(a_n) \in K_p \ \Rightarrow \ (\sigma_n) \in K_q$$

to be valid, for every sequence (a_n), where the sequence (σ_n) is given by (5)*, is that the following conditions, for every n,*

$$d_{n,n} - qd_{n-1,n-1} = 0,\ d_{n,n-k} - qd_{n-1,n-k-1} \geq 0\ (k = 1, \dots, n-1)$$
$$d_{n,0} \geq 0,$$

hold, where

$$d_{n,k} = \sum_{j=0}^{k} p^{k-j} p_n, j.$$

Proof. We have

$$L_q(\sigma_{n-1}) = \sigma_n - q\sigma_{n-1} = \sum_{j=0}^{n} p_{n,n-j}a_j - q\sum_{j=0}^{n-1} p_{n-1,n-1-j}a_j = \sum_{j=0}^{n} w_j a_j$$

where $w_j = p_{n,n-j} - qp_{n-1,n-1-j}(j = 0, 1, \dots, n-1)$ and $w_n = p_{n,0}$. Using Theorem 1, we obtain Theorem 4.

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