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A Concept of Synchronicity Associated with Convex Functions in Linear Spaces and Applications

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A CONCEPT OF SYNCHRONICITY ASSOCIATED WITH CONVEX FUNCTIONS IN LINEAR SPACES AND APPLICATIONS

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ABSTRACT. A concept of synchronicity associated with convex functions in linear spaces and a Čebyšev type inequality are given. Applications for norms, semi-inner products and for convex functions of several real variables are also given.

1. INTRODUCTION

The Jensen inequality for convex functions plays a crucial role in the Theory of Inequalities due to the fact that other inequalities such as that arithmetic mean-geometric mean inequality, Hölder and Minkowski inequalities, Ky Fan's inequality etc. can be obtained as particular cases of it.

Let C be a convex subset of the linear space X and f a convex function on C. If $\mathbf{p} = (p_1, \ldots, p_n)$ is a probability sequence and $\mathbf{x} = (x_1, \ldots, x_n) \in C^n$, then

$$(1.1) \qquad f\left(\sum_{i=1}^{n} p_i x_i\right) \leq \sum_{i=1}^{n} p_i f(x_i),$$

is well known in the literature as Jensen's inequality.

For refinements of the Jesen inequality and applications related to Ky Fan's inequality, the arithmetic mean-geometric mean inequality, the generalised triangle inequality, the f-divergence measures etc. see [1]-[7].

Assume that $f : X \to \mathbb{R}$ is a *convex function* on the real linear space X. Since for any vectors $x, y \in X$ the function $g_{x,y} : \mathbb{R} \to \mathbb{R}$, $g_{x,y}(t) := f(x + ty)$ is convex it follows that the following limits exist

$$\nabla_{+(-)} f(x)(y) := \lim_{t \to 0+(-)} \frac{f(x + ty) - f(x)}{t}$$

and they are called the *right(left) Gâteaux derivatives* of the function f in the point x over the direction y.

It is obvious that for any $t > 0 > s$ we have

$$(1.2) \qquad \frac{f(x + ty) - f(x)}{t} \geq \nabla_+ f(x)(y) = \inf_{t>0}\left[\frac{f(x + ty) - f(x)}{t}\right]$$

$$\geq \sup_{s<0}\left[\frac{f(x + sy) - f(x)}{s}\right] = \nabla_- f(x)(y) \geq \frac{f(x + sy) - f(x)}{s}$$

for any $x, y \in X$ and, in particular,

$$(1.3) \qquad \nabla_- f(u)(u - v) \geq f(u) - f(v) \geq \nabla_+ f(v)(u - v)$$

for any $u, v \in X$. We call this *the gradient inequality* for the convex function f. It will be used frequently in the sequel in order to obtain various results related to Jensen's inequality.

The following properties are also of importance:

$$(1.4) \qquad \nabla_+ f(x)(-y) = -\nabla_- f(x)(y),$$

and

$$(1.5) \qquad \nabla_{+(-)} f(x)(\alpha y) = \alpha \nabla_{+(-)} f(x)(y)$$

for any $x, y \in X$ and $\alpha \geq 0$.

The right Gâteaux derivative is *subadditive* while the left one is *superadditive*, i.e.,

$$(1.6) \qquad \nabla_+ f(x)(y + z) \leq \nabla_+ f(x)(y) + \nabla_+ f(x)(z)$$

and

$$(1.7) \qquad \nabla_- f(x)(y + z) \geq \nabla_- f(x)(y) + \nabla_- f(x)(z)$$

for any $x, y, z \in X$.

Some natural examples can be provided by the use of normed spaces.

Assume that $(X, \|\cdot\|)$ is a real normed linear space. The function $f : X \to \mathbb{R}$, $f(x) := \frac{1}{2} \|x\|^2$ is a convex function which generates *the superior* and *the inferior semi-inner products*

$$\langle y, x \rangle_{s(i)} := \lim_{t \to 0+(-)} \frac{\|x + ty\|^2 - \|x\|^2}{t}.$$

For a comprehensive study of the properties of these mappings in the Geometry of Banach Spaces see the monograph [6].

For the convex function $f_p : X \to \mathbb{R}$, $f_p(x) := \|x\|^p$ with $p > 1$, we have

$$\nabla_{+(-)} f_p(x)(y) = \begin{cases} p \|x\|^{p-2} \langle y, x \rangle_{s(i)} & \text{if } x \neq 0 \\ 0 & \text{if } x = 0 \end{cases}$$

for any $y \in X$.

If $p = 1$, then we have

$$\nabla_{+(-)} f_1(x)(y) = \begin{cases} \|x\|^{-1} \langle y, x \rangle_{s(i)} & \text{if } x \neq 0 \\ +(-) \|y\| & \text{if } x = 0 \end{cases}$$

for any $y \in X$.

This class of functions will be used to illustrate the inequalities obtained in the general case of convex functions defined on an entire linear space.

In the recent paper [9] the following refinement and reverse of the Jensen inequality in terms of the gradient have been obtained:

Theorem 1. *Let $f : X \to \mathbb{R}$ be a convex function defined on a linear space X. Then for any n-tuple of vectors $\mathbf{x} = (x_1, ..., x_n) \in X^n$ and any probability distribution $\mathbf{p} = (p_1, ..., p_n) \in \mathbb{P}^n$ we have the inequality*

$$(1.8) \quad \sum_{k=1}^{n} p_k \nabla_- f(x_k)(x_k) - \sum_{k=1}^{n} p_k \nabla_- f(x_k) \left(\sum_{i=1}^{n} p_i x_i \right)$$

$$\geq \sum_{i=1}^{n} p_i f(x_i) - f\left(\sum_{i=1}^{n} p_i x_i \right)$$

$$\geq \sum_{k=1}^{n} p_k \nabla_+ f\left(\sum_{i=1}^{n} p_i x_i \right)(x_k) - \nabla_+ f\left(\sum_{i=1}^{n} p_i x_i \right)\left(\sum_{i=1}^{n} p_i x_i \right) \geq 0.$$

A particular case of interest is for $f(x) = \|x\|^p$ where $(X, \|\cdot\|)$ is a normed linear space. Then for any $p \geq 1$, for any n-tuple of vectors $\mathbf{x} = (x_1, ..., x_n) \in X^n$ and any probability distribution $\mathbf{p} = (p_1, ..., p_n) \in \mathbb{P}^n$ with $\sum_{i=1}^{n} p_i x_i \neq 0$ we have the inequality

$$(1.9) \quad \sum_{i=1}^{n} p_i \|x_i\|^p - \left\| \sum_{i=1}^{n} p_i x_i \right\|^p$$

$$\geq p \left\| \sum_{i=1}^{n} p_i x_i \right\|^{p-2} \left[\sum_{k=1}^{n} p_k \left\langle x_k, \sum_{j=1}^{n} p_j x_j \right\rangle_s - \left\| \sum_{i=1}^{n} p_i x_i \right\|^2 \right] \geq 0.$$

If $p \geq 2$ the inequality holds for any n-tuple of vectors and probability distribution.

Also, for any $p \geq 1$, for any n-tuple of vectors $\mathbf{x} = (x_1, ..., x_n) \in X^n \setminus \{(0, ..., 0)\}$ and any probability distribution $\mathbf{p} = (p_1, ..., p_n) \in \mathbb{P}^n$ we have the inequality

$$(1.10) \quad p \left[\sum_{k=1}^{n} p_k \|x_k\|^p - \sum_{k=1}^{n} p_k \|x_k\|^{p-2} \left\langle \sum_{i=1}^{n} p_i x_i, x_k \right\rangle_i \right]$$

$$\geq \sum_{i=1}^{n} p_i \|x_i\|^p - \left\| \sum_{i=1}^{n} p_i x_i \right\|^p.$$

Motivated by the above results we introduce in this paper a class of sequences associated with convex functions in linear spaces and establish a Čebyšev type inequality and some new inequalities for convex functions. Applications for norms, semi-inner products and for convex functions of several real variables are also given.

2. $\nabla f -$SYNCHRONICITY

Consider $f : X \to \mathbb{R}$ a convex function on the linear space X. We also assume that $u = (u_1, \ldots, u_n)$ and $v = (v_1, \ldots, v_n)$ are two $n-$tuples of vectors with $u_i, v_i \in X$, $i \in \{1, \ldots, n\}$.

Definition 1. *We say that v is $\nabla f -$synchronous with u if*

$$(2.1) \qquad \nabla_- f(u_k)(v_k - v_j) \geq \nabla_+ f(u_j)(v_k - v_j)$$

for any $k, j \in \{1, \ldots, n\}$. If the inequality is reversed in (2.1) for each $k, j \in \{1, \ldots, n\}$, then we say that v is $\nabla f -$asynchronous with u.

We notice that in general, if v is $\nabla f-$asynchronous with u, this does not imply that u is $\nabla f-$synchronous with v.

As general examples of such convex functions we can consider $f(x) = \|x\|^p$, $p \geq 1$ where $(X, \|\cdot\|)$ is a normed linear space. Since (see Introduction)

$$\nabla_- f(x)(y) = p \|x\|^{p-2} \langle y, x \rangle_i \quad \text{for } x, y \in X \quad \text{with } x \neq 0;$$

$$\nabla_- f(0)(y) = \begin{cases} 0 & \text{if } p > 1 \\ \\ -\|y\| & \text{if } p = 1 \end{cases}, \quad \text{for } y \in X;$$

$$\nabla_+ f(x)(y) = p \|x\|^{p-2} \langle y, x \rangle_s \quad \text{for } x, y \in X \quad \text{with } x \neq 0;$$

$$\nabla_+ f(0)(y) = \begin{cases} 0 & \text{if } p > 1 \\ \\ \|y\| & \text{if } p = 1 \end{cases}, \quad \text{for } y \in X,$$

where $\langle \cdot, \cdot \rangle_s$ is the *superior semi-inner product* and $\langle \cdot, \cdot \rangle_i$ is the *inferior semi-inner product*, then we can define the following concepts of synchronicity for the two $n-$tuples of vectors $u = (u_1, \ldots, u_n)$ and $v = (v_1, \ldots, v_n)$.

Let $p \geq 1$ and $u, v \in X^n$ be as above. We say that v *is* $p - \nabla-$*synchronous with* u if

$$(2.2) \qquad \|u_k\|^{p-2} \langle v_k - v_j, u_k \rangle_i \geq \|u_j\|^{p-2} \langle v_k - v_j, u_j \rangle_s$$

for any $k, j \in \{1, \ldots, n\}$.

We observe that for $p \in [1, 2)$ we should assume that $u_k \neq 0$ for $k \in \{1, \ldots, n\}$. For $p = 2$, the equation (2.2) reduces to

$$(2.3) \qquad \langle v_k - v_j, u_k \rangle_i \geq \langle v_k - v_j, u_j \rangle_s \quad \text{for any } k, j \in \{1, \ldots, n\}.$$

If $(X, \|\cdot\|)$ is a smooth normed space, meaning that the norm is Gâteaux differentiable on any $x \in X$, $x \neq 0$ and if we denote by $[\cdot, \cdot]$ the semi-inner product generating the norm $\|\cdot\|$ (see [6, pp. 19-20]), then the fact that v is $p - \nabla-$synchronous with u means that

$$(2.4) \qquad \|u_k\|^{p-2} [v_k - v_j, u_k] \geq \|u_j\|^{p-2} [v_k - v_j, u_j]$$

for any $k, j \in \{1, \ldots, n\}$. For $p = 2$, we have

$$(2.5) \qquad [v_k - v_j, u_k] \geq [v_k - v_j, u_j] \quad \text{for any } k, j \in \{1, \ldots, n\}.$$

Moreover, if the norm $\|\cdot\|$ is generated by an inner product $\langle \cdot, \cdot \rangle$, then v is $p - \nabla-$synchronous with u means that

$$(2.6) \qquad \left\langle v_k - v_j, \|u_k\|^{p-2} u_k - \|u_j\|^{p-2} v_j \right\rangle \geq 0 \quad \text{for any } k, j \in \{1, \ldots, n\}$$

while for $p = 2$, it reduces to

$$(2.7) \qquad \langle v_k - v_j, u_k - u_j \rangle \geq 0 \quad \text{for any } k, j \in \{1, \ldots, n\},$$

which is the concept of *synchronous sequences* in inner product spaces that has been introduced in [13]. For some inequalities for synchronous sequences in inner product spaces, see [13] and [14].

As some natural examples of synchronous sequences in inner product spaces, we can consider the sequences $\{x_i\}_{i \in \mathbb{N}}$ and $\{Ax_i\}_{i \in \mathbb{N}}$ where $A : X \to X$ is a positive linear operator on X, i.e., $\langle Ax, x \rangle \geq 0$ for any $x \in X$.

For a convex function $f : X \to \mathbb{R}$ we define $\tilde{\nabla} f(\cdot)(\cdot)$ as

$$(2.8) \qquad \tilde{\nabla} f(x)(y) := \frac{1}{2} \left[\nabla_- f(x)(y) + \nabla_+ f(x)(y) \right],$$

where $x, y \in X$.

We observe that for f as above, we have *the homogeneity property*:

$$(2.9) \qquad \tilde{\nabla} f(x)(\alpha y) = \alpha \tilde{\nabla} f(x)(y) \quad \text{for any } x, y \in X,$$

and any $\alpha \in \mathbb{R}$.

The following inequality for $\nabla - f-$synchronous sequences holds.

Theorem 2. *Assume that v is $\nabla - f-$synchronous with u and $\mathbf{p} = (p_1, \ldots, p_n)$ is a probability distribution. Then*

$$(2.10) \qquad \sum_{i=1}^n p_i \tilde{\nabla} f(u_i)(v_i) \geq \sum_{i,j=1}^n p_i p_j \tilde{\nabla} f(u_i)(v_j).$$

Proof. Since $\nabla_+ (\cdot)(\cdot)$ is subadditive in the second variable, then we have

$$(2.11) \qquad \nabla_+ f(u_i)(v_i - v_j) \geq \nabla_+ f(u_i)(v_i) - \nabla_+ f(u_i)(v_j)$$

for any $i, j \in \{1, \ldots, n\}$.

Also, by the fact that $\nabla_- (\cdot)(\cdot)$ is superadditive in the second variable, we have that

$$(2.12) \qquad \nabla_- f(u_i)(v_i) - \nabla_- f(u_i)(v_j) \geq \nabla_- f(u_i)(v_i - v_j)$$

for all $i, j \in \{1, \ldots, n\}$.

Now, by (2.11), (2.12) and by the definition of $\nabla - f-$synchronicity, we deduce that

$$\nabla_- f(u_i)(v_i) - \nabla_- f(u_i)(v_j) \geq \nabla_+ f(u_i)(v_i) - \nabla_+ f(u_i)(v_j),$$

which is equivalent with

$$(2.13) \qquad \nabla_- f(u_i)(v_i) + \nabla_+ f(u_i)(v_j) \geq \nabla_+ f(u_i)(v_i) + \nabla_- f(u_i)(v_j)$$

for all $i, j \in \{1, \ldots, n\}$.

Therefore, by multiplying (2.13) with $p_i p_j \geq 0$ and summing over i and j from 1 to n, we get

$$(2.14) \quad \sum_{i=1}^n p_i \nabla_- f(u_i)(v_i) + \sum_{j=1}^n p_j \nabla_+ f(u_i)(v_j)$$

$$\geq \sum_{i,j=1}^n p_i p_j \nabla_+ f(u_i)(v_i) + \sum_{i,j=1}^n p_i p_j \nabla_- f(u_i)(v_j).$$

Now, observe that

$$\sum_{j=1}^n p_j \nabla_+ f(u_j)(v_j) = \sum_{i=1}^n p_i \nabla_+ f(u_i)(v_i)$$

and

$$\sum_{i,j=1}^n p_i p_j \nabla_+ f(u_j)(v_i) = \sum_{i,j=1}^n p_i p_j \nabla_+ f(u_i)(v_j),$$

which, by (2.14) divided by 2, provides the desired result (2.10). $\qquad \square$

Corollary 1. *With the assumptions of Theorem 2 and, if in addition $\tilde{\nabla} f(u_i)(\cdot)$ is additive for any $i \in \{1, \ldots, n\}$, then we have*

$$(2.15) \qquad \sum_{i=1}^{n} p_i \tilde{\nabla} f(u_i)(v_i) \geq \sum_{i,j=1}^{n} p_i p_j \tilde{\nabla} f(u_i) \left(\sum_{j=1}^{n} p_j u_j \right).$$

Remark 1. *If f is Gâteaux differentiable at the points u_i, $i \in \{1, \ldots, n\}$, then $\tilde{\nabla} f(u_i)(\cdot) = \nabla f(u_i)(\cdot)$ and is therefore linear on X. With this assumption, the inequality (2.15) holds with ∇ instead of $\tilde{\nabla}$. Moreover, there are examples of convex functions defined on linear spaces for which $\tilde{\nabla} f(x)(\cdot)$ is linear for any $x \neq 0$ without the function f being Gâteaux differentiable at that point (see [6, pp. 44-45]).*

Following [15], we consider the $g-$*semi-inner product* $\langle \cdot, \cdot \rangle_g : X \times X \to \mathbb{R}$ defined by

$$\langle y, x \rangle_g := \frac{1}{2} \left[\langle y, x \rangle_i + \langle y, x \rangle_s \right], \quad x, y \in X.$$

Utilising this notation, we have the following conditional inequality for semi-inner products and norms in normed linear spaces.

Proposition 1. *Let $(X, \|\cdot\|)$ be a normed linear space, $u = (u_1, \ldots, u_n)$, $v = (v_1, \ldots, v_n) \in X^n$ and $p \geq 1$. If*

$$(2.16) \qquad \|u_k\|^{p-2} \langle v_k - v_j, u_k \rangle_i \geq \|u_j\|^{p-2} \langle v_k - v_j, u_j \rangle_s$$

for any $k, j \in \{1, \ldots, n\}$, then

$$(2.17) \qquad \sum_{k=1}^{n} p_k \|u_k\|^{p-2} \langle v_k, u_k \rangle_g \geq \sum_{k,j=1}^{n} p_k p_j \|u_k\|^{p-2} \langle v_j, u_k \rangle_g$$

for any $\mathbf{p}$ a probability distribution. If $p \geq 2$, then we should have in (2.16) all $u_k \neq 0$. If $p = 2$ and

$$(2.18) \qquad \langle v_k - v_j, u_k \rangle_i \geq \langle v_k - v_j, u_j \rangle_s$$

for any $k, j \in \{1, \ldots, n\}$, then

$$(2.19) \qquad \sum_{k=1}^{n} p_k \langle v_k, u_k \rangle_g \geq \sum_{k,j=1}^{n} p_k p_j \langle v_j, u_k \rangle_g,$$

for any $\mathbf{p}$ a probability distribution.

As a particular case of interest, we state the following result that holds in inner product spaces.

Corollary 2. *Let $(X, \langle \cdot, \cdot \rangle)$ be a real inner product space, $u = (u_1, \ldots, u_n)$, $v = (v_1, \ldots, v_n) \in X^n$ and $p \geq 1$. If*

$$(2.20) \qquad \left\langle v_k - v_j, \|u_k\|^{p-2} u_k - \|u_j\|^{p-2} v_j \right\rangle \geq 0$$

for any $k, j \in \{1, \ldots, n\}$, then

$$(2.21) \qquad \sum_{k=1}^{n} p_k \|u_k\|^{p-2} \langle v_k, u_k \rangle \geq \left\langle \sum_{j=1}^{n} p_j u_j, \sum_{k=1}^{n} p_k \|u_k\|^{p-2} u_k \right\rangle$$

for any $\mathbf{p}$ a probability distribution.

Remark 2. *We observe that if the $n-$tuples u and v above are synchronous, i.e.,*

$$(2.22) \qquad \langle v_k - v_j, u_k - u_j \rangle \geq 0 \quad \text{for any } j, k \in \{1, \ldots, n\},$$

then we have the following Čebyšev type inequality

$$(2.23) \qquad \sum_{k=1}^{n} p_k \langle v_k, u_k \rangle \geq \left\langle \sum_{k=1}^{n} p_k v_k, \sum_{k=1}^{n} p_k u_k \right\rangle.$$

This result was first obtained in $[13]$.

3. Inequalities for Convex Functions

The following result for convex functions may be stated:

Theorem 3. *Let $f : X \to \mathbb{R}$ be a convex function on the linear space X and $x, y \in X^n$. Let $\mathbf{p}$ be a probability distribution so that $\sum_{i=1}^{n} p_i x_i = \sum_{i=1}^{n} p_i y_i$. If $x - y$ is $\tilde{\nabla} - f-$synchronous with y and $\tilde{\nabla} f(y_i)(\cdot)$ is additive for each $i \in \{1, \ldots, n\},$ then we have the inequality:*

$$(3.1) \qquad \sum_{i=1}^{n} p_i f(x_i) \geq \sum_{i=1}^{n} p_i f(y_i).$$

Proof. Since f is convex, then for any $x, y \in X$ we have

$$(3.2) \qquad f(x) - f(y) \geq \nabla_+ f(y)(x - y) \geq \tilde{\nabla} f(y)(x - y).$$

Then from (3.2) we have the inequality:

$$(3.3) \qquad f(x_i) - f(y_i) \geq \tilde{\nabla} f(y_i)(x_i - y_i)$$

for each $i \in \{1, \ldots, n\}$.

Now, if we multiply (3.3) with $p_i \geq 0$ and then sum over i from 1 to n, we get

$$(3.4) \qquad \sum_{i=1}^{n} p_i f(x_i) - \sum_{i=1}^{n} p_i f(y_i) \geq \sum_{i=1}^{n} p_i \tilde{\nabla} f(y_i)(x_i - y_i).$$

Now, if we use Corollary 1 for $u_i = y_i$ and $v_i = x_i - y_i$, $i \in \{1, \ldots, n\}$, we deduce the inequality

$$(3.5) \qquad \sum_{i=1}^{n} p_i \tilde{\nabla} f(y_i)(x_i - y_i) \geq \sum_{i=1}^{n} p_i \tilde{\nabla} f(y_i) \left(\sum_{i=1}^{n} p_i (x_i - y_i) \right)$$

$$= \sum_{i=1}^{n} p_i \tilde{\nabla} f(y_i)(0) = 0.$$

Combining (3.4) with (3.5), we deduce the desired inequality (3.1). $\qquad \square$

Remark 3. *It is clear that if f is Gâteaux differentiable at all the points y_i, $i \in \{1, \ldots, n\}$, then $\tilde{\nabla} f(y_i)(\cdot) = \nabla f(y_i)(\cdot)$, $i \in \{1, \ldots, n\}$, which are linear on X.*

In the case of Gâteaux differentiable functions, we can state the following result as well.

Theorem 4. *Let $f : X \to \mathbb{R}$ be a convex and Gâteaux differentiable function on the linear space X. Assume that $x, y \in X^n$ and $\mathbf{p}$ is a probability distribution. If $x - y$ is $\tilde{\nabla} - f-$synchronous with y and*

$$\sum_{i=1}^{n} p_i x_i - \sum_{i=1}^{n} p_i y_i \in \bigcap_{i=1}^{n} \ker \left(\nabla f \left(y_i \right) \left(\cdot \right) \right),$$

then

$$(3.6) \qquad \sum_{i=1}^{n} p_i f \left(x_i \right) \geq \sum_{i=1}^{n} p_i f \left(y_i \right).$$

The proof is as in that of Theorem 3 when in (3.5) we take into account that

$$\nabla f \left(y_i \right) \left(\sum_{i=1}^{n} p_i x_i - \sum_{i=1}^{n} p_i y_i \right) = 0$$

for all $i \in \{1, \ldots, n\}$ since

$$\sum_{i=1}^{n} p_i x_i - \sum_{i=1}^{n} p_i y_i \in \bigcap_{i=1}^{n} \ker \left(\nabla f \left(y_i \right) \left(\cdot \right) \right).$$

The following result in smooth normed linear spaces may be stated.

Proposition 2. *Let $(X, \|\cdot\|)$ be a smooth normed linear space and let $[\cdot, \cdot]$ be the semi-inner product that generates its norm $\|\cdot\|$. If $x, y \in X^n$ and $p \geq 1$ are such that*

$$(3.7) \qquad \|y_k\|^{p-2} \left[x_k - y_k - x_j + y_j, y_k \right] \geq \|y_j\|^{p-2} \left[x_k - y_k - x_j + y_j, y_j \right]$$

for any $k, j \in \{1, \ldots, n\}$, then for any probability distribution $\mathbf{p}$ with the property that

$$(3.8) \qquad \sum_{j=1}^{n} p_j x_j = \sum_{j=1}^{n} p_j y_j$$

we have the inequality

$$(3.9) \qquad \sum_{k=1}^{n} p_k \|x_k\|^{p} \geq \sum_{k=1}^{n} p_k \|y_k\|^{p}.$$

If $p \in [1, 2)$ we shall assume that $y_k \neq 0$ for $k \in \{1, \ldots, n\}$.
If $p = 2$ and

$$(3.10) \qquad \left[x_k - y_k - x_j + y_j, y_k \right] \geq \left[x_k - y_k - x_j + y_j, y_j \right]$$

for any $k, j \in \{1, \ldots, n\}$, then for any probability distribution $\mathbf{p}$ satisfying (3.8), we have

$$(3.11) \qquad \sum_{k=1}^{n} p_k \|x_k\|^{2} \geq \sum_{k=1}^{n} p_k \|y_k\|^{2}.$$

The case of inner product spaces is incorporated in:

Corollary 3. *Let $(X; \langle \cdot, \cdot \rangle)$ be an inner product space. If $x, y \in X^n$ and $p \geq 1$ are such that*

$$(3.12) \qquad \left\langle x_k - x_j, \|y_k\|^{p-2} y_k - \|y_j\|^{p-2} y_j \right\rangle \geq \left\langle y_k - y_j, \|y_k\|^{p-2} y_k - \|y_j\|^{p-2} y_j \right\rangle$$

for any $k, j \in \{1, \ldots, n\}$, then for any $\mathbf{p}$ satisfying (3.8), we have the inequality (3.9).

If $p \in [1, 2)$, then we shall assume that $y_k \neq 0$, $k \in \{1, \ldots, n\}$.

If $p = 2$ and

$$(3.13) \qquad \langle x_k - x_j, y_k - y_j \rangle \geq \|y_k - y_j\|^2 \quad \text{for any } k, j \in \{1, \ldots, n\}$$

then for any $\mathbf{p}$ satisfying (3.8), we have the inequality (3.11).

4. Applications for Convex Functions on $\mathbb{R}^m$

Now, consider an open and convex set C in the real linear space $\mathbb{R}^m$, $m \geq 1$. For a convex and differentiable function $f : C \to \mathbb{R}$, we have

$$(4.1) \qquad \nabla f(x)(y) = \left\langle \frac{\partial f(x)}{\partial x}, y \right\rangle, \quad x \in C, \ y \in \mathbb{R}^m,$$

where

$$\frac{\partial f(x)}{\partial x} = \left(\frac{\partial f(x)}{\partial x^1}, \ldots, \frac{\partial f(x)}{\partial x^m} \right), \quad x = \left(x^1, \ldots, x^m \right) \in C$$

and $\langle \cdot, \cdot \rangle$ is the usual inner product in $\mathbb{R}^m$, i.e., $\langle u, v \rangle = \sum_{k=1}^m u^i \cdot v^i$, where $u = \left(u^1, \ldots, u^m \right)$ and $v = \left(v^1, \ldots, v^m \right) \in \mathbb{R}^m$.

Now, if $\mathbf{v} := (v_1, \ldots, v_n) \in \mathbb{R}^m$ and $\mathbf{u} := (u_1, \ldots, u_n) \in C^m$, then we say that $\mathbf{v}$ is $\nabla - f$−synchronous with $\mathbf{u}$ if

$$(4.2) \qquad \left\langle \frac{\partial f(u_k)}{\partial x} - \frac{\partial f(u_j)}{\partial x}, v_k - v_j \right\rangle \geq 0 \quad \text{for any } k, j \in \{1, \ldots, n\}.$$

The following result may be stated.

Proposition 3. *Let $f : C \to \mathbb{R}$ be a differentiable convex function on the open and convex set $C \subseteq \mathbb{R}^m$. If $\mathbf{v} := (v_1, \ldots, v_n) \in \mathbb{R}^m$ and $\mathbf{u} := (u_1, \ldots, u_n) \in C^m$ are such that $\mathbf{v}$ is $\nabla - f$−synchronous with $\mathbf{u}$, then for any probability distribution $\mathbf{p} = (p_1, \ldots, p_n)$, we have the inequality*

$$(4.3) \qquad \sum_{i=1}^n p_i \left\langle \frac{\partial f(u_i)}{\partial x}, v_i \right\rangle \geq \left\langle \sum_{i=1}^n p_i \frac{\partial f(u_i)}{\partial x}, \sum_{i=1}^n p_i v_i \right\rangle.$$

The proof is obvious by Corollary 1.

Now, if $u_k = \left(u_k^1, \ldots, u_k^m \right)$, $k \in \{1, \ldots, n\}$ and $v_k = \left(v_k^1, \ldots, v_k^m \right)$, then

$$(4.4) \qquad \left\langle \frac{\partial f(u_k)}{\partial x} - \frac{\partial f(u_j)}{\partial x}, v_k - v_j \right\rangle = \sum_{\ell=1}^m \left(\frac{\partial f(u_k)}{\partial x} - \frac{\partial f(u_j)}{\partial x} \right) \left(v_k^\ell - v_j^\ell \right).$$

Remark 4. *The above relation (4.4) shows that a sufficient condition for $\mathbf{v}$ to be $\nabla - f$−synchronous with $\mathbf{u}$ is that all the sequences $\left\{ \frac{\partial f(u_k)}{\partial x_\ell} \right\}_{k=1,\ldots,n}$ and $\left\{ v_k^\ell \right\}_{k=1,\ldots,n}$ are synchronous, where $\ell \in \{1, \ldots, m\}$, i.e.,*

$$(4.5) \qquad \left(\frac{\partial f(u_k)}{\partial x} - \frac{\partial f(u_j)}{\partial x} \right) \left(v_k^\ell - v_j^\ell \right) \geq 0 \quad \text{for any } k, j \in \{1, \ldots, n\}$$

and for all $\ell \in \{1, \ldots, m\}$.

The following result is an obvious consequence of Theorem 4.

Proposition 4. *Let $f : C \to \mathbb{R}$ be a differentiable convex function on the open and convex set $C \subseteq \mathbb{R}^m$. If $\mathbf{x} = (x_1, \ldots, x_n) \in \mathbb{R}^m$ and $\mathbf{y} = (y_1, \ldots, y_n) \in C^m$ are such that*

$$(4.6) \qquad \left\langle \frac{\partial f(y_k)}{\partial x} - \frac{\partial f(y_j)}{\partial x}, x_k - x_j \right\rangle \geq \left\langle \frac{\partial f(y_k)}{\partial x} - \frac{\partial f(y_j)}{\partial x}, y_k - y_j \right\rangle,$$

for each $k, j \in \{1, \ldots, n\}$, then for any probability distribution $\mathbf{p} = (p_1, \ldots, p_n)$ with

$$(4.7) \qquad \sum_{i=1}^n p_i x_i = \sum_{i=1}^n p_i y_i$$

we have the inequality

$$(4.8) \qquad \sum_{i=1}^n p_i f(x_i) \geq \sum_{i=1}^n p_i f(y_i).$$

Remark 5. *As above, a sufficient condition for (4.6) to hold is that the sequences $\left\{ \frac{\partial f(y_k)}{\partial x_\ell} \right\}_{k=1,\ldots,n}$ and $\left\{ x_k^\ell - y_k^\ell \right\}_{k=1,\ldots,n}$ are synchronous for each $\ell \in \{1, \ldots, m\}$.*

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