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ON SOME HERMITE-HADAMARD INEQUALITIES TYPE FOR FUNCTIONS WHOSE POWER OF THE ABSOLUTE VALUE OF DERIVATIVES ARE (α, m)-CONVEX

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Abstract. In this paper we give a lemma which help us to formulate some inequalities of Hermite-Hadamard type for functions whose q-powers of the absolute values of second derivative is (α, m)- convex or s-convex. What become this inequalities for other type of convexities as P-convex or quasi-convex functions will be studied also here.

1. Introduction

We recall the well-known Holder′s integral inequality which can be stated as follows, see [14], [9] and then Theorem 2.1, see [9].

Theorem 1. *If $f(x) \geq 0,\ g(x) \geq 0$ and $f(x) \in L^p[a,b],\ g(x) \in L^q[a,b]$ and $p > 1,\ \frac{1}{p} + \frac{1}{q} = 1$, then*

$$\int_a^b f(x)g(x)dx \leq \left(\int_a^b f^p(x)dx\right)^{\frac{1}{p}} \left(\int_a^b g^q(x)dx\right)^{\frac{1}{q}}. \tag{1}$$

Theorem 2. *If the conditions of Theorem 1 are satisfied and $t > 0$ then*

$$\int_a^b f(x)g(x)dx \leq C(p,t) \left(\int_a^b f^p(x)dx\right)^{\frac{1}{p}} \left(\int_a^b g^q(x)dx\right)^{\frac{1}{q}}. \tag{2}$$

where $C(p,t) = \frac{1}{p}t^{\frac{1}{p}-1} + (1-\frac{1}{p})t^{\frac{1}{p}}$.

We also need to recall the definition of s-convex functions in the second sense and Theorem 2.3 from [1].

Definition 1. *A function $f : I \subseteq \mathbb{R}_+ \to \mathbb{R}_+$, where $\mathbb{R}_+ = [0,\infty)$ is said to be s-convex on I if the inequality $f(\alpha x + \beta y) \leq \alpha^s f(x) + \beta^s f(y)$ holds for all $x,\ y \in I$ and $\alpha,\ \beta \in [0,1]$ with $\alpha + \beta = 1$ and for some fixed $s \in (0,1]$.*

Now we recall the notion of quasi-convex functions which also generalizes the notion of convex function and then we present Theorem 2.3 from [2].

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Definition 2. *A function $f : [a, b] \to \mathbb{R}$ is said quasi-convex on $[a, b]$ if*

$$f(\lambda x + (1-\lambda)y) \leq \sup\{f(x), f(y)\},$$

for all $x,\ y \in [a, b]$ and $\lambda \in [0, 1]$.

Definition 3. *The function $f : [0, b] \to \mathbb{R}$ is said to be m-convex where $m \in [0, 1]$ if for every $x, y \in [0, b]$ and $t \in [0, 1]$ we have:*

$$f(tx + m(1-t)y) \leq tf(x) + m(1-t)f(y).$$

As a generalization of previous notion we have the following:

Definition 4. *The function $f : [0, b] \to \mathbb{R},\ b > 0$ is said to be (α, m) -convex, where $(\alpha, m) \in [0, 1]^2$ if we have*

$$f(tx + m(1-t)y) \leq t^{\alpha} f(x) + m(1-t^{\alpha})f(y)$$

for all $x, y \in [0, b]$ and $t \in [0, 1]$.

Definition 5. *Let $I \subseteq \mathbb{R}$ be an interval. The function $f : I \to \mathbb{R}$ is said to belong to the class $P(I)$ (or P- convex) if it is nonnegative and for all $x,\ y \in I$ and $\lambda \in [0, 1]$ satisfies the inequality*

$$f(\lambda x + (1-\lambda)y) \leq f(x) + f(y).$$

2. Hermite-Hadamard's type inequalities for (α, m)- convex functions ans s-convex functions in the second sense

In the following we will give a lemma similar to Lemma 1 from [13] but for f'' instead of f'.

Lemma 1. *Let $f : I \subseteq \mathbb{R} \to \mathbb{R}$ be a twice differentiable function on I°, the interior if I where $a,\ b \in I$ with $a < b$. If $f'' \in L[a, b]$ then the following equality holds:*

$$-\frac{f(\frac{3a+b}{4}) + f(\frac{a+3b}{4})}{2} + \frac{1}{b-a}\int_a^b f(x)dx =$$

$$= \frac{(b-a)^2}{128}[\int_0^1 t^2 f''(t\frac{3a+b}{4} + (1-t)a)dt + \int_0^1 (t-1)^2 f''(t\frac{a+b}{2} + (1-t)\frac{3a+b}{4})dt +$$

$$+ \int_0^1 t^2 f''(t\frac{a+3b}{4} + (1-t)\frac{a+b}{2})dt + \int_0^1 (t-1)^2 f''(tb + (1-t)\frac{a+3b}{4})dt].$$

Proof. We shall denote

$$I_1 = \int_0^1 t^2 f''(t\frac{3a+b}{4} + (1-t)a)dt,$$

$$I_2 = \int_0^1 (t-1)^2 f''(t\frac{a+b}{2} + (1-t)\frac{3a+b}{4})dt,$$

$$I_3 = \int_0^1 t^2 f''(t\frac{a+3b}{4} + (1-t)\frac{a+b}{2})dt$$

and

$$I_4 = \int_0^1 (t-1)^2 f''(tb + (1-t)\frac{a+3b}{4})dt.$$

Then by calculuses we note that

$$I_1 = \frac{4}{b-a} f^{'}(\frac{3a+b}{4}) - \frac{32}{(b-a)^2} f(\frac{3a+b}{4}) + \frac{32}{(b-a)^2}\int_0^1 f(t\frac{3a+b}{4} + (1-t)a)dt,$$

$$I_2 = -\frac{4}{b-a} f^{'}(\frac{3a+b}{4}) - \frac{32}{(b-a)^2} f(\frac{3a+b}{4}) + \frac{32}{(b-a)^2}\int_0^1 f(t\frac{a+b}{2} + (1-t)\frac{3a+b}{4})dt,$$

$$I_3 = \frac{4}{b-a} f^{'}(\frac{a+3b}{4}) - \frac{32}{(b-a)^2} f(\frac{a+3b}{4}) + \frac{32}{(b-a)^2}\int_0^1 f(t\frac{a+3b}{4} + (1-t)\frac{a+b}{2})dt,$$

$$I_4 = -\frac{4}{b-a} f^{'}(\frac{a+3b}{4}) - \frac{32}{(b-a)^2} f(\frac{a+3b}{4}) + \frac{32}{(b-a)^2}\int_0^1 f(tb + (1-t)\frac{a+3b}{4})dt,$$

and using the substitutions $x = t\frac{3a+b}{4} + (1-t)a$, $x = t\frac{a+b}{2} + (1-t)\frac{3a+b}{4}$, $x = t\frac{a+3b}{4} + (1-t)\frac{a+b}{2}$ and $x = tb + (1-t)\frac{a+3b}{4}$ respectively and summing we will obtain:

$$-\frac{64}{(b-a)^2} f(\frac{3a+b}{4}) - \frac{64}{(b-a)^2} f(\frac{a+3b}{4}) + \frac{128}{(b-a)^3}\int_a^b f(x)dx = I_1 + I_2 + I_2 + I_4.$$

∎

We will use this lemma for obtaining a new Hermite-Hadamard type inequality similar to Theorem 2 from [13].

Theorem 3. *Let $f : I \subseteq \mathbb{R} \to \mathbb{R}$ be a twice differentiable function on I°, the interior if I where $a,\ b \in I$ with $a < b$ and $f^{''} \in L_1[a,b]$. If $|f^{''}|^q$ is (α, m)- convex on $[a,b]$ for some fixed $q > 1$ then the following equality holds:*

$$|\frac{f(\frac{3a+b}{4}) + f(\frac{a+3b}{4})}{2} - \frac{1}{b-a}\int_a^b f(x)dx| \leq \frac{(b-a)^2}{128}\left(\frac{1}{\alpha+1}\right)^{\frac{1}{q}}\left(\frac{1}{2p+1}\right)^{\frac{1}{p}}\cdot$$

$$\cdot[C(p,l_1)(|f^{''}(\frac{3a+b}{4})|^q + \alpha m|f^{''}(\frac{a}{m})|^q)^{\frac{1}{q}} + C(p,l_2)(m|f^{''}(\frac{a+b}{2m})|^q + \alpha|f^{''}(\frac{3a+b}{4})|^q)^{\frac{1}{q}}$$

$$+C(p,l_3)(|f^{''}(\frac{a+3b}{4})|^q + m\alpha|f^{''}(\frac{a+b}{2m})|^q)^{\frac{1}{q}} + C(p,l_4)(m|f^{''}(\frac{b}{m})|^q + \alpha|f^{''}(\frac{a+3b}{4})|^q)^{\frac{1}{q}}],$$

where $C(p,l)$ is as in Theorem 2.

Proof. We will apply Lemma 1, Theorem 2 and the definition of (α, m)- convex functions for $|f^{''}|^q$ obtaining the following:

$$|\frac{f(\frac{3a+b}{4}) + f(\frac{a+3b}{4})}{2} - \frac{1}{b-a}\int_a^b f(x)dx| \leq$$

$$\leq \frac{(b-a)^2}{128}[C(p,l_1)\left(\frac{1}{2p+1}\right)^{\frac{1}{p}}\left(\int_0^1 (t^\alpha|f^{''}(\frac{3a+b}{4})|^q + m(1-t^\alpha)|f^{''}(\frac{a}{m})|^q)dt\right)^{\frac{1}{q}} +$$

$$+C(p,l_2)\left(\frac{1}{2p+1}\right)^{\frac{1}{p}}\left(\int_0^1 (mt^\alpha|f^{''}(\frac{a+b}{2m})|^q + (1-t^\alpha)|f^{''}(\frac{3a+b}{4})|^q)dt\right)^{\frac{1}{q}} +$$

$$+C(p,l_3)\left(\frac{1}{2p+1}\right)^{\frac{1}{p}}\left(\int_0^1 (t^\alpha|f^{''}(\frac{a+3b}{4})|^q + m(1-t^\alpha)|f^{''}(\frac{a+b}{2m})|^q)dt\right)^{\frac{1}{q}} +$$

$$+C(p,l_4)\left(\frac{1}{2p+1}\right)^{\frac{1}{p}}\left(\int_0^1 (mt^\alpha|f^{''}(\frac{b}{m})|^q + (1-t^\alpha)|f^{''}(\frac{a+3b}{4})|^q)dt\right)^{\frac{1}{q}}].$$

Then by calculuses we obtain the inequality from theorem.

∎

Another variant of previous theorem is the following:

Theorem 4. *Let $f : I \subseteq \mathbb{R} \to \mathbb{R}$ be a twice differentiable function on I°, the interior if I where $a,\ b \in I$ with $a < b$ and $f^{''} \in L_1[a,b]$. If $|f^{''}|^q$ is (α, m)- convex on $[a,b]$ for some fixed $q > 1$ then the following equality holds:*

$$|\frac{f(\frac{3a+b}{4}) + f(\frac{a+3b}{4})}{2} - \frac{1}{b-a}\int_a^b f(x)dx| \leq \frac{(b-a)^2}{128}\left(\frac{1}{\alpha+q+1}\right)^{\frac{1}{q}}\left(\frac{1}{p+1}\right)^{\frac{1}{p}}\cdot$$

$$\cdot[C(p,l_1)(|f^{''}(\frac{3a+b}{4})|^q + \frac{\alpha m}{q+1}|f^{''}(\frac{a}{m})|^q)^{\frac{1}{q}} +$$

$$+C(p,l_2)(m\frac{\alpha q}{\alpha+q}B(\alpha,q)|f^{''}(\frac{a+b}{2m})|^q + (\frac{\alpha+q+1}{q+1} - \frac{\alpha q}{\alpha+q}B(\alpha,q))|f^{''}(\frac{3a+b}{4})|^q)^{\frac{1}{q}}$$

$$+C(p,l_3)(|f^{''}(\frac{a+3b}{4})|^q + \frac{m\alpha}{q+1}|f^{''}(\frac{a+b}{2m})|^q)^{\frac{1}{q}} +$$

$$+C(p,l_4)(m\frac{\alpha q}{\alpha+q}B(\alpha,q)|f^{''}(\frac{b}{m})|^q + (\frac{\alpha+q+1}{q+1} - \frac{\alpha q}{\alpha+q}B(\alpha,q))|f^{''}(\frac{a+3b}{4})|^q)^{\frac{1}{q}}],$$

where $C(p,l)$ is as in Theorem 2 and $B(\alpha,q) = \int_0^1 x^{\alpha-1}(1-x)^{q-1}$ is the Euler′s function.

Proof. By using Lemma 1 we will have:

$$|\frac{f(\frac{3a+b}{4}) + f(\frac{a+3b}{4})}{2} - \frac{1}{b-a}\int_a^b f(x)dx| \leq \frac{(b-a)^2}{128}[\int_0^1 t^2|f^{''}(t\frac{3a+b}{4} + (1-t)a)|dt +$$

$$+\int_0^1 (t-1)^2|f^{''}(t\frac{a+b}{2} + (1-t)\frac{3a+b}{4})|dt + \int_0^1 t^2|f^{''}(t\frac{a+3b}{4} + (1-t)\frac{a+b}{2})|dt +$$

$$+\int_0^1 (t-1)^2|f^{''}(tb + (1-t)\frac{a+3b}{4})|dt].$$

Now using Theorem 2 we obtain:

$$|\frac{f(\frac{3a+b}{4}) + f(\frac{a+3b}{4})}{2} - \frac{1}{b-a}\int_a^b f(x)dx| \leq \frac{(b-a)^2}{128}\cdot$$

$$\cdot[C(p,l_1)(\int_0^1 t^p dt)^{\frac{1}{p}}(\int_0^1 t^q|f^{''}(t\frac{3a+b}{4} + (1-t)a)|^q dt)^{\frac{1}{q}} +$$

$$+C(p,l_2)(\int_0^1 (1-t)^p dt)^{\frac{1}{p}}(\int_0^1 (1-t)^q|f^{''}(t\frac{a+b}{2} + (1-t)\frac{3a+b}{4})|^q dt)^{\frac{1}{q}} +$$

$$+C(p,l_3)(\int_0^1 t^p dt)^{\frac{1}{p}}(\int_0^1 t^q|f^{''}(t\frac{a+3b}{4} + (1-t)\frac{a+b}{2})|^q dt)^{\frac{1}{q}} +$$

$$+C(p,l_4)(\int_0^1 (1-t)^p dt)^{\frac{1}{p}}(\int_0^1 (1-t)^q|f^{''}(tb + (1-t)\frac{a+3b}{4})|^q dt)^{\frac{1}{q}}]$$

and using the definition of (α, m)- convexity for $|f^{''}|^q$ we will have

$$|\frac{f(\frac{3a+b}{4}) + f(\frac{a+3b}{4})}{2} - \frac{1}{b-a}\int_a^b f(x)dx| \leq \frac{(b-a)^2}{128}\left(\frac{1}{p+1}\right)^{\frac{1}{p}}\cdot$$

$$\cdot[C(p,l_1)(\int_0^1 t^q(t^\alpha|f^{''}(\frac{3a+b}{4})|^q + m(1-t^\alpha)|f^{''(\frac{a}{m})}|^q)dt)^{\frac{1}{q}} +$$

$$+C(p,l_2)(\int_0^1 (1-t)^q(mt^\alpha|f''(\frac{a+b}{2m})|^q+(1-t^\alpha)|f''(\frac{3a+b}{4})|^q)dt)^{\frac{1}{q}}+$$
$$+C(p,l_3)(\int_0^1 t^q(t^\alpha|f''(\frac{a+3b}{4})|^q+m(1-t^\alpha)|f''^{(\frac{a+b}{2m})}|^q)dt)^{\frac{1}{q}}+$$
$$+C(p,l_4)(\int_0^1 (1-t)^q(mt^\alpha|f''(\frac{b}{m})|^q+(1-t^\alpha)|f''(\frac{a+3b}{4})|^q)dt)^{\frac{1}{q}}].$$

By calculuses we find the inequality from the theorem.
∎

For functions with the power of the second derivative in absolute value s-convex we will obtain the following result:

Theorem 5. *Let $f : I \subseteq [0,\infty) \to \mathbb{R}$ be a twice differentiable function on I°, the interior if I where $a,\ b \in I$ with $a < b$ and $f'' \in L_1[a,b]$. If $|f''|^{p/(p-1)}$, $(p > 1)$ is s- convex on $[a,b]$ for some fixed $s \in (0,1]$ then the following equality holds:*

$$|\frac{f(\frac{3a+b}{4})+f(\frac{a+3b}{4})}{2}-\frac{1}{b-a}\int_a^b f(x)dx| \leq \frac{(b-a)^2}{128}\left(\frac{1}{p+1}\right)^{\frac{1}{p}}\left(\frac{1}{s+q+1}\right)^{\frac{1}{q}}\cdot$$
$$\cdot[C(p,l_1)(|f''(\frac{3a+b}{4})|^q+\frac{sq}{s+q}B(s,q)|f''(\frac{a+b}{2})|^q)^{\frac{1}{q}}+$$
$$+C(p,l_2)(\frac{sq}{s+q}B(s,q)|f''(\frac{a+b}{2})|^q+|f''(\frac{3a+b}{4})|^q)^{\frac{1}{q}}+$$
$$+C(p,l_3)(|f''(\frac{a+3b}{4})|^q+\frac{sq}{s+q}B(s,q)|f''(\frac{a+b}{2})|^q)^{\frac{1}{q}}+$$
$$+C(p,l_4)(\frac{sq}{s+q}B(s,q)|f''(b)|^q+|f''(\frac{a+3b}{4})|^q)^{\frac{1}{q}}],$$

where $\frac{1}{p}+\frac{1}{q}=1$, $C(p,l)$ is as in Theorem 2 and $B(\alpha,q)=\int_0^1 x^{\alpha-1}(1-x)^{q-1}$ is the Euler's function.

Proof. We use Lemma 1, Theorem 2 and the definition of s-convexity in the second sense and the proof will be as in the previous theorem. ∎

3. Hermite-Hadamard's type inequalities for P- convex functions ans quasi-convex functions

If we consider now P- convexity instead of (α,m)- convexity then we will obtain the following result:

Theorem 6. *Let $f : I \to \mathbb{R}$ be a twice differentiable function on I°. Assume that $p \in \mathbb{R}$, $p > 1$ such that $|f''|^{\frac{p}{p-1}|}$ is a P - convex function on I. Suppose that $a,\ b \in I^\circ$ with $a < b$ and $f'' \in L_1[a,b]$. Then we have:*

$$|\frac{f(\frac{3a+b}{4})+f(\frac{a+3b}{4})}{2}-\frac{1}{b-a}\int_a^b f(x)dx| \leq \frac{(b-a)^2}{128}\left(\frac{1}{p+1}\right)^{\frac{1}{p}}\left(\frac{1}{q+1}\right)^{\frac{1}{q}}\cdot$$
$$\cdot[C(p,l_1)(|f''(\frac{3a+b}{4})|^q+|f''(a)|^q)^{\frac{1}{q}}+C(p,l_2)(|f''(\frac{a+b}{2})|^q+|f''(\frac{a+3b}{4})|^q)^{\frac{1}{q}}+$$
$$+C(p,l_3)(|f''(\frac{a+3b}{4})|^q+|f''(\frac{a+b}{2})|^q)^{\frac{1}{q}}+C(p,l_4)(|f''(b)|^q+|f''(\frac{a+3b}{4})|^q)^{\frac{1}{q}}],$$

where $\frac{1}{p}+\frac{1}{q}=1$, *and* $C(p,l)$, $l>0$ *is as in Theorem 2.*

Proof. We apply Lemma 1 and Theorem 2.
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Theorem 7. *Let* $f: I\subseteq[0,\infty)\to\mathbb{R}$ *be a twice differentiable function on* I°. *Assume that* $p\in\mathbb{R}$, $p>1$ *such that* $|f''|^{\frac{p}{p-1}|}$ *is a quasi-convex function on* I. *Suppose that* $a,\ b\in I^{\circ}$ *with* $a<b$ *and* $f''\in L^1[a,b]$. *Then we have:*

$$|\frac{f(\frac{3a+b}{4})+f(\frac{a+3b}{4})}{2}-\frac{1}{b-a}\int_a^b f(x)dx|\leq\frac{(b-a)^2}{128}\left(\frac{1}{p+1}\right)^{\frac{1}{p}}\left(\frac{1}{q+1}\right)^{\frac{1}{q}}\cdot$$

$$\cdot[C(p,l_1)\sup\{|f''(\frac{3a+b}{4})|,|f''(a)|\}+C(p,l_2)\sup\{|f''(\frac{a+b}{2})|,|f''(\frac{a+3b}{4})|\}+$$

$$+C(p,l_3)\sup\{|f''(\frac{a+3b}{4})|,|f''(\frac{a+b}{2})|\}+C(p,l_4)\sup\{|f''(b)|,|f''(\frac{a+3b}{4})|\}],$$

where $\frac{1}{p}+\frac{1}{q}=1$, *and* $C(p,l)$, $l>0$ *is as in Theorem 2.*

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