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ON SOME NEW INEQUALITIES OF HERMITE-HADAMARD-FEJÉR TYPE INVOLVING CONVEX FUNCTIONS

Abstract. In this paper, we establish some inequalities of Hermite-Hadamard-Fejér type for m-convex functions and s-convex functions.

1. Introduction

If $f : [a, b] \to \mathbb{R}$ is a convex function then

$$f\left(\frac{a+b}{2}\right) \leq \frac{1}{b-a}\int_a^b f(x)dx \leq \frac{f(a)+f(b)}{2} \tag{1.1}$$

is known as Hermite-Hadamard inequality.

Fejér [14] gave a generalization of the inequalities (1.1) as the following:

If $f : [a, b] \to \mathbb{R}$ is a convex function, and $g : [a, b] \to \mathbb{R}$ is nonnegative, integrable and symmetric about $\frac{a+b}{2}$, then

$$f\left(\frac{a+b}{2}\right)\int_a^b g(x)dx \leq \int_a^b f(x)g(x)dx \leq \frac{f(a)+f(b)}{2}\int_a^b g(x)dx. \tag{1.2}$$

For some results which generalize, improve, and extend the inequalities (1.1) and (1.2) see [1]–[12], [14]–[16], [19]–[23].

DEFINITION 1 (see [6, 13, 18]). *A 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:*

$$f(tx + m(1-t)y) \leq tf(x) + m(1-t)f(y). \tag{1.3}$$

We denote the set of all m-convex functions on $[0, b]$ by $K_m(b)$.

Dragomir and Toader [13] (see also [6]) proved the following two theorems:

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THEOREM 1. *Let $f : [0,\infty) \to \mathbb{R}$ be an m-convex function with $m \in (0,1]$. If $0 \le a < b < \infty$ and $f \in L_1[0,b]$ then*

$$\int_a^b f(x)dx \le (b-a)\min\left\{\frac{f(a)+mf(\frac{b}{m})}{2}, \frac{f(b)+mf\left(\frac{a}{m}\right)}{2}\right\}. \tag{1.4}$$

THEOREM 2. *Let f, m, a and b be defined as in Theorem 1. If f is also differentiable on $(0,\infty)$ then*

$$\left[\frac{f(mb)}{m} - \frac{b-a}{2}f'(mb)\right](b-a) \le \int_a^b f(x)dx \le \frac{1}{2}[(b-ma)f(b) - (a-mb)f(a)]. \tag{1.5}$$

The following two theorems are due to Dragomir [6]:

THEOREM 3. *Let f be defined as in Theorem 1. Then*

$$f\left(\frac{a+b}{2}\right)(b-a) \le \int_a^b \frac{f(x)+mf\left(\frac{x}{m}\right)}{2}dx \le \frac{b-a}{8}\left[f(a)+f(b)+2m\left(f\left(\frac{a}{m}\right)+f\left(\frac{b}{m}\right)\right) + m^2\left(f\left(\frac{a}{m^2}\right)+f\left(\frac{b}{m^2}\right)\right)\right]. \tag{1.6}$$

THEOREM 4. *Let $f : [0,\infty) \to \mathbb{R}$ be an $m-$convex function with $m \in (0,1]$. If $f \in L_1[am,b]$, where $0 \le a < b$, then*

$$\frac{1}{m+1}\left[\int_a^{mb} f(x)dx + \frac{mb-a}{b-ma}\int_{ma}^b f(x)dx\right] \le (mb-a)\frac{f(a)+f(b)}{2}.$$

REMARK 1. A misprint of (1.6) in the original paper has been corrected here.

DEFINITION 2 (see [9, 10, 17]). Let $0 < s \le 1$. A function $f : [0,\infty) \to \mathbb{R}$ is said to be s-convex in the first sense, if for every $x, y \in [0,\infty)$ and $\alpha, \beta \ge 0$ with $\alpha^s + \beta^s = 1$, we have:

$$f(\alpha x + \beta y) \le \alpha^s f(x) + \beta^s f(y). \tag{1.7}$$

We denote the set of all s-convex functions in the first sense by K_s^1.

DEFINITION 3 (see [9, 10, 17]). Let $0 < s \le 1$. A function $f : [0,\infty) \to \mathbb{R}$ is said to be $s-$convex in the second sense, if for every $x, y \in [0,\infty)$ and $\alpha, \beta \ge 0$ with $\alpha + \beta = 1$ we have the inequality (1.7). The set of all s-convex functions in the second sense is denoted by K_s^2.

Dragomir and Fitzpatrick [9, 10] proved the following two theorems:

THEOREM 5. *Let $f \in K_s^1$ and $a, b \in [0, \infty)$ with $a < b$. Then*

$$(b-a)f\left[2^{-\frac{1}{s}}(a+b)\right] \leq \int_a^b f(x)dx \tag{1.8}$$

and

$$f\left(\frac{a+b}{2^{\frac{1}{s}-1}}\right) \leq \int_0^1 f\left(\frac{a+b}{2^{\frac{1}{s}}}\left[t^{\frac{1}{s}} + (1-t)^{\frac{1}{s}}\right]\right)dt \tag{1.9}$$

$$\leq \int_0^1 f(at^{\frac{1}{s}} + b(1-t)^{\frac{1}{s}})dt \leq \frac{f(a)+f(b)}{2}.$$

THEOREM 6. *Let $f \in K_s^2$ and $a, b \in [0, \infty)$ with $a < b$. Then*

$$2^{s-1}(b-a)f\left(\frac{a+b}{2}\right) \leq \int_a^b f(x)dx \leq \frac{(b-a)(f(a)+f(b))}{(s+1)}. \tag{1.10}$$

In this paper, we shall establish some generalizations of Theorems 1–6.

2. Main results

Throughout this section, let $g : [a, b] \to \mathbb{R}$ be nonnegative, integrable and symmetric about $\frac{a+b}{2}$.

THEOREM 7. *Let f, m, a and b be defined as in Theorem 1. Then*

$$\int_a^b f(x)g(x)dx \leq \min\left\{\frac{f(a)+mf(\frac{b}{m})}{2}, \frac{f(b)+mf\left(\frac{a}{m}\right)}{2}\right\}\int_a^b g(x)dx. \tag{2.1}$$

Proof. Since f is m-convex and g is nonnegative, integrable and symmetric about $\frac{a+b}{2}$, we have

$$\int_a^b f(x)g(x)dx = \frac{1}{2}\left[\int_a^b f(x)g(x)dx + \int_a^b f(a+b-x)g(a+b-x)dx\right] \tag{2.2}$$

$$= \frac{1}{2}\int_a^b [f(x) + f(a+b-x)]g(x)dx$$

$$= \frac{1}{2}\int_a^b \left[f\left(\frac{b-x}{b-a}a + m\frac{x-a}{b-a}\cdot\frac{b}{m}\right)\right.$$

$$+ f\left(\frac{x-a}{b-a}a + m\frac{b-x}{b-a}\cdot\frac{b}{m}\right)\Bigg] g(x)dx$$

$$\leq \frac{1}{2}\int_a^b \Bigg[\frac{b-x}{b-a}f(a) + m\frac{x-a}{b-a}f\left(\frac{b}{m}\right)$$

$$+ \frac{x-a}{b-a}f(a) + m\frac{b-x}{b-a}f\left(\frac{b}{m}\right)\Bigg] g(x)dx$$

$$= \frac{f(a) + mf(\frac{b}{m})}{2}\int_a^b g(x)dx.$$

On the other hand,

$$\int_a^b f(x)g(x)dx = \frac{1}{2}\int_a^b [f(x) + f(a+b-x)]\, g(x)dx \tag{2.3}$$

$$= \frac{1}{2}\int_a^b \Bigg[f\left(m\frac{b-x}{b-a}\cdot\frac{a}{m} + \frac{x-a}{b-a}b\right)$$

$$+f\left(m\frac{x-a}{b-a}\cdot\frac{a}{m} + \frac{b-x}{b-a}b\right)\Bigg] g(x)dx$$

$$\leq \frac{1}{2}\int_a^b \Bigg[m\frac{b-x}{b-a}f\left(\frac{a}{m}\right) + \frac{x-a}{b-a}f(b)$$

$$+m\frac{x-a}{b-a}f\left(\frac{a}{m}\right) + \frac{b-x}{b-a}f(b)\Bigg] g(x)dx$$

$$= \frac{mf\left(\frac{a}{m}\right) + f(b)}{2}\int_a^b g(x)dx.$$

The inequality (2.1) follows immediately from (2.2) and (2.3). ∎

REMARK 2. If we choose $g(x) \equiv 1$, then Theorem 7 reduces to Theorem 1.

REMARK 3. If $m = 1$, then the inequality (2.1) reduces to the second inequality of (1.2) where $0 \leq a < b < \infty$.

In order to prove our second theorem, we need the following lemma:

LEMMA 1 (see [6] or [13]). *Let f is differentiable on $[0, b]$. Then $f \in K_m(b)$ if and only if*

$$f(x) - mf(y) \leq f'(x)(x - my) \tag{2.4}$$

for $x, y \in [0, b]$.

THEOREM 8. *Let f, m, a and b be defined as in Theorem 2. Then*

$$\left[\frac{f(mb)}{m} - \frac{b-a}{2}f'(mb)\right]\int_a^b g(x)dx \le \int_a^b f(x)g(x)dx$$

$$\le \int_a^b [(x-ma)f'(x) + mf(a)]g(x)dx. \tag{2.5}$$

Proof. By Lemma 1, for $x \in [a, b]$, we have

$$f(mb) - mf(x) \le f'(mb)(mb - mx)$$

and

$$f(mb) - mf(a+b-x) \le f'(mb)[mb - m(a+b-x)],$$

so that

$$\frac{f(mb)}{m} - (b-x)f'(mb) \le f(x) \tag{2.6}$$

and

$$\frac{f(mb)}{m} - (x-a)f'(mb) \le f(a+b-x). \tag{2.7}$$

If we add the inequalities (2.6) and (2.7) then

$$\frac{2f(mb)}{m} - (b-a)f'(mb) \le f(x) + f(a+b-x) \tag{2.8}$$

for all $x \in [a, b]$. Since g is nonnegative, integrable and symmetric about $\frac{a+b}{2}$, multiplying (2.8) by $\frac{g(x)}{2}$, and integrating the resulting inequalities on $[a, b]$ yields

$$\left[\frac{f(mb)}{m} - \frac{b-a}{2}f'(mb)\right]\int_a^b g(x)dx$$

$$\le \frac{1}{2}\int_a^b [f(x)g(x) + f(a+b-x)g(x)]dx$$

$$= \frac{1}{2}\left[\int_a^b f(x)g(x)dx + \int_a^b f(a+b-x)g(a+b-x)dx\right]$$

$$= \int_a^b f(x)g(x)dx.$$

This proves the first inequality in (2.5). Putting in (2.4) $y = a$, we have for $x \ge ma$

$$(x-ma)f'(x) + mf(a) \ge f(x). \tag{2.9}$$

Multiplying (2.9) by $g(x)$ and integrating over x on $[a,b]$, we obtain the second inequality in (2.5). This completes the proof. ∎

REMARK 4. If we choose $g(x) \equiv 1$ then Theorem 8 reduces to Theorem 2.

THEOREM 9. *Let f, m, a and b be defined as in Theorem 1. Then*

$$
\begin{aligned}
(2.10)\quad f\left(\frac{a+b}{2}\right)\int_a^b g(x)dx &\le \int_a^b \frac{f(x)+mf\left(\frac{x}{m}\right)}{2}g(x)dx \\
&\le \frac{1}{8}\left[f(a)+f(b)+2m\left(f\left(\frac{a}{m}\right)+f\left(\frac{b}{m}\right)\right)\right. \\
&\qquad \left.+m^2\left(f\left(\frac{a}{m^2}\right)+f\left(\frac{b}{m^2}\right)\right)\right]\int_a^b g(x)dx \\
&\le \frac{m^2\left[f\left(\frac{a}{m^2}\right)+f\left(\frac{b}{m^2}\right)\right]}{2}\int_a^b g(x)dx.
\end{aligned}
$$

Proof. Since f is $m-$convex, $f \in L_1[a,b]$ and g is nonnegtive, integrable and symmetric about $\frac{a+b}{2}$, we have

$$
\begin{aligned}
(2.11)\quad & f\left(\frac{a+b}{2}\right)\int_a^b g(x)dx \\
&= \int_a^b f\left[\frac{1}{2}(a+b-x)+\frac{m}{2}\cdot\frac{x}{m}\right]g(x)dx \\
&\le \int_a^b \left[\frac{1}{2}f(a+b-x)+\frac{m}{2}f\left(\frac{x}{m}\right)\right]g(x)dx \\
&= \int_a^b \frac{1}{2}\left[f(a+b-x)g(a+b-x)+mf\left(\frac{x}{m}\right)g(x)\right]dx \\
&= \frac{1}{2}\left[\int_a^b f(x)g(x)dx+\int_a^b mf\left(\frac{x}{m}\right)g(x)dx\right] = \int_a^b \frac{f(x)+mf\left(\frac{x}{m}\right)}{2}g(x)dx, \\
&= \frac{1}{4}\left[\int_a^b f(x)g(x)dx+\int_a^b f(a+b-x)g(a+b-x)dx\right. \\
&\qquad \left.+\int_a^b mf\left(\frac{x}{m}\right)g(x)dx+\int_a^b mf\left(\frac{a+b-x}{m}\right)g(a+b-x)dx\right]
\end{aligned}
$$

$$= \frac{1}{8}\left[2\int_a^b f(x)g(x)dx + 2\int_a^b f(a+b-x)g(x)dx \right.$$

$$\left. + 2\int_a^b mf\left(\frac{x}{m}\right)g(x)dx + 2\int_a^b mf\left(\frac{a+b-x}{m}\right)g(x)dx\right]$$

$$= \frac{1}{8}\left[\int_a^b f\left(\frac{b-x}{b-a}a + \frac{x-a}{b-a}m\frac{b}{m}\right)g(x)dx\right.$$

$$+ \int_a^b f\left(\frac{b-x}{b-a}m\frac{a}{m} + \frac{x-a}{b-a}b\right)g(x)dx$$

$$+ \int_a^b f\left(\frac{x-a}{b-a}a + \frac{b-x}{b-a}m\frac{b}{m}\right)g(x)dx$$

$$+ \int_a^b f\left(\frac{x-a}{b-a}m\frac{a}{m} + \frac{b-x}{b-a}b\right)g(x)dx$$

$$+ \int_a^b mf\left(\frac{b-x}{b-a}\frac{a}{m} + \frac{x-a}{b-a}m\frac{b}{m^2}\right)g(x)dx$$

$$+ \int_a^b mf\left(\frac{b-x}{b-a}m\frac{a}{m^2} + \frac{x-a}{b-a}\frac{b}{m}\right)g(x)dx$$

$$+ \int_a^b mf\left(\frac{x-a}{b-a}\cdot\frac{a}{m} + \frac{b-x}{b-a}\cdot m\cdot\frac{b}{m^2}\right)g(x)dx$$

$$\left.+ \int_a^b mf\left(\frac{x-a}{b-a}m\frac{a}{m^2} + \frac{b-x}{b-a}\cdot\frac{b}{m}\right)g(x)dx\right]$$

$$\leq \frac{1}{8}\left\{\int_a^b\left[\frac{b-x}{b-a}f(a) + m\frac{x-a}{b-a}f\left(\frac{b}{m}\right)\right]g(x)dx\right.$$

$$+ \int_a^b\left[m\frac{b-x}{b-a}f\left(\frac{a}{m}\right) + \frac{x-a}{b-a}f(b)\right]g(x)dx$$

$$+ \int_a^b\left[\frac{x-a}{b-a}f(a) + m\frac{b-x}{b-a}f\left(\frac{b}{m}\right)\right]g(x)dx$$

$$+ \int_a^b\left[m\frac{x-a}{b-a}f\left(\frac{a}{m}\right) + \frac{b-x}{b-a}f(b)\right]g(x)dx$$

$$+ \int_a^b m\left[\frac{b-x}{b-a}f\left(\frac{a}{m}\right) + m\frac{x-a}{b-a}f\left(\frac{b}{m^2}\right)\right]g(x)dx$$

$$+\int_a^b m\left[m\frac{b-x}{b-a}f\left(\frac{a}{m^2}\right)+\frac{x-a}{b-a}f\left(\frac{b}{m}\right)\right]g(x)dx$$

$$+\int_a^b m\left[\frac{x-a}{b-a}f\left(\frac{a}{m}\right)+m\frac{b-x}{b-a}f\left(\frac{b}{m^2}\right)\right]g(x)dx$$

$$+\int_a^b m\left[m\frac{x-a}{b-a}f\left(\frac{a}{m^2}\right)+\frac{b-x}{b-a}f\left(\frac{b}{m}\right)\right]g(x)dx\Bigg\}$$

$$= \frac{1}{8}\left[f(a)+f(b)+2m\left(f\left(\frac{a}{m}\right)+f\left(\frac{b}{m}\right)\right)\right. \tag{2.12}$$

$$\left.+m^2\left(f\left(\frac{a}{m^2}\right)+f\left(\frac{b}{m^2}\right)\right)\right]\int_a^b g(x)dx$$

$$= \frac{\int_a^b g(x)dx}{8}\left\{f\left(0\cdot a+m\cdot\frac{a}{m}\right)+f\left(0\cdot b+m\cdot\frac{b}{m}\right)\right.$$

$$+2m\left[f\left(0\cdot\frac{a}{m}+m\cdot\frac{a}{m^2}\right)+f\left(0\cdot\frac{b}{m}+m\cdot\frac{b}{m^2}\right)\right]$$

$$\left.+m^2\left[f\left(\frac{a}{m^2}\right)+f\left(\frac{b}{m^2}\right)\right]\right\}$$

$$\leq \frac{\int_a^b g(x)dx}{8}\left\{mf\left(\frac{a}{m}\right)+mf\left(\frac{b}{m}\right)+3m^2\left[f\left(\frac{a}{m^2}\right)+f\left(\frac{b}{m^2}\right)\right]\right\}$$

$$= \frac{\int_a^b g(x)dx}{8}\left\{mf\left(0\cdot\frac{a}{m}+m\frac{a}{m^2}\right)+mf\left(0\cdot\frac{b}{m}+m\frac{b}{m^2}\right)\right.$$

$$\left.+3m^2\left[f\left(\frac{a}{m^2}\right)+f\left(\frac{b}{m^2}\right)\right]\right\}$$

$$\leq \frac{m^2\left[f\left(\frac{a}{m^2}\right)+f\left(\frac{b}{m^2}\right)\right]}{2}\int_a^b g(x)dx. \tag{2.13}$$

The inequalities (2.10) follow from (2.11), (2.12) and (2.13). ∎

REMARK 5. If we choose $g(x)\equiv 1$, then Theorem 9 reduces to Theorem 3.

REMARK 6. If $m=1$, then the inequalities (2.10) reduce to the inequalities (1.2) when $0\leq a<b<\infty$.

THEOREM 10. *Suppose that $f:[0,\infty)\to\mathbb{R}$ is an $m-$convex function with $f\in L_1[ma,b]$ and $k:[ma,b]\to\mathbb{R}$ is nonnegative, integrable and symmetric about $\frac{ma+b}{2}$ with $\int_{ma}^b k(x)dx>0$, where $m\in[0,1]$ and $0\leq a<b$.*

(a) *If $a<mb$ and $h:[a,mb]\to\mathbb{R}$ is nonnegative, integrable and symmetric about $\frac{a+mb}{2}$ with $\int_a^{mb}h(x)dx>0$, then*

$$\frac{1}{m+1}\left(\frac{\int_a^{mb} f(x)h(x)dx}{\int_a^{mb} h(x)dx}+\frac{\int_{ma}^{b} f(x)k(x)dx}{\int_{ma}^{b} k(x)dx}\right)\leq\frac{f(a)+f(b)}{2}. \tag{2.14}$$

(b) *If* $mb<a$ *and* $h:[mb,a]\to\mathbb{R}$ *is nonnegative, integrable and symmetric about* $\frac{a+mb}{2}$ *with* $\int_{mb}^{a} h(x)dx>0$ *then the inequality (2.14) also holds.*

Proof. (a) Since f is $m-$convex, $f\in L_1[ma,b]$, k is nonnegative, integrable, symmetric about $\frac{ma+b}{2}$ with $\int_{ma}^{b} k(x)dx>0$, we have

$$\begin{aligned}\int_{ma}^{b} f(x)k(x)dx &= \frac{\int_{ma}^{b} f(x)k(x)dx+\int_{ma}^{b} f(ma+b-x)k(ma+b-x)dx}{2}\\ &= \frac{\int_{ma}^{b}[f(x)+f(ma+b-x)]k(x)dx}{2} \qquad (2.15)\\ &= \frac{1}{2}\int_{ma}^{b}\left[f\left(\frac{b-x}{b-ma}ma+\frac{x-ma}{b-ma}b\right)\right.\\ &\qquad \left.+f\left(\frac{x-ma}{b-ma}ma+\frac{b-x}{b-ma}b\right)\right]k(x)dx\\ &\leq \frac{1}{2}\int_{ma}^{b}\left[m\frac{b-x}{b-ma}f(a)+\frac{x-ma}{b-ma}f(b)\right.\\ &\qquad \left.+m\frac{x-ma}{b-ma}f(a)+\frac{b-x}{b-ma}f(b)\right]k(x)dx\\ &= \frac{mf(a)+f(b)}{2}\int_{ma}^{b} k(x)dx.\end{aligned}$$

Similarly, we have

$$\int_a^{mb} f(x)h(x)dx\leq\frac{f(a)+mf(b)}{2}\int_a^{mb} h(x)dx \tag{2.16}$$

The inequality (2.14) follows immediately from (2.15) and (2.16).

The proof of part (b) is similar to that of part (a). ∎

REMARK 7. If we choose $h(x)\equiv 1$ and $k(x)\equiv 1$ then Theorem 10 reduces to Theorem 4.

REMARK 8. If $m=1$ and $h(x)=k(x)=g(x)$ on $[a,b]$ then the inequality (2.14) reduces to the second inequality of (1.2) when $0\leq a<b<\infty$.

In order to prove our next theorem, we need the following lemma:

LEMMA 2 ([17]). *If* $0<s<1$ *and* $f\in K_s^1$, *then* f *is nondecreasing on* $[0,\infty)$.

THEOREM 11. *Let f, a and b be defined as in Theorem 5. Then*

$$f\left[2^{-\frac{1}{s}}(a+b)\right]\int_a^b g(x)dx \le \int_a^b f(x)g(x)dx \tag{2.17}$$

and

$$\begin{aligned} f\left(\frac{a+b}{2^{\frac{2}{s}-1}}\right)&\int_a^b g(x)dx \\ &\le \int_a^b \left\{ f\left[\left(\frac{1}{2}\cdot\frac{b-x}{b-a}\right)^{\frac{1}{s}} + \left(\frac{1}{2}\cdot\frac{x-a}{b-a}\right)^{\frac{1}{s}}(a+b)\right]\right\} g(x)dx \\ &\le \int_a^b f\left[a\left(\frac{b-x}{b-a}\right)^{\frac{1}{s}} + b\left(\frac{x-a}{b-a}\right)^{\frac{1}{s}}\right] g(x)dx \\ &\le \frac{f(a)+f(b)}{2}\int_a^b g(x)dx. \end{aligned} \tag{2.18}$$

Proof. Since $f \in K_s^1$ and g is nonnegative, integrable and symmetric about $\frac{a+b}{2}$, then we have

$$\begin{aligned} f\left[2^{-\frac{1}{s}}(a+b)\right]\int_a^b g(x)dx &= \int_a^b f\left[2^{-\frac{1}{s}}x + 2^{-\frac{1}{s}}(a+b-x)\right] g(x)dx \\ &\le \int_a^b \left[\frac{1}{2}f(x) + \frac{1}{2}f(a+b-x)\right] g(x)dx \\ &= \frac{1}{2}\left[\int_a^b f(x)g(x)dx + \int_a^b f(a+b-x)g(x)dx\right] \\ &= \frac{1}{2}\left[\int_a^b f(x)g(x)dx + \int_a^b f(a+b-x)g(a+b-x)dx\right] \\ &= \int_a^b f(x)g(x)dx. \end{aligned}$$

This proves (2.17).

Next, if $s = 1$ then (2.18) is (1.2). Let $0 < s < 1$, and $\alpha, \beta \ge 0$ then

$$\left(\frac{\alpha+\beta}{2}\right)^{\frac{1}{s}} \le \frac{1}{2}\left(\alpha^{\frac{1}{s}} + \beta^{\frac{1}{s}}\right).$$

Now, by Lemma 2, f is nondecreasing on $[0,\infty)$. Since g is nonnegative

integrable and symmetric about $\frac{a+b}{2}$, we have

$$
\begin{aligned}
(2.19)\qquad & f\left(\frac{a+b}{2^{\frac{2}{s}-1}}\right)\int_a^b g(x)dx \\
&= \int_a^b f\left[\left(\frac{1}{2}\cdot\frac{b-x}{2(b-a)}+\frac{1}{2}\cdot\frac{x-a}{2(b-a)}\right)^{\frac{1}{s}}2(a+b)\right]g(x)dx \\
&\le \int_a^b f\left[\left(\frac{1}{2}\left(\frac{b-x}{2(b-a)}\right)^{\frac{1}{s}}+\frac{1}{2}\left(\frac{x-a}{2(b-a)}\right)^{\frac{1}{s}}\right)2(b+a)\right]g(x)dx \\
&= \int_a^b f\left[\left(\frac{b-x}{2(b-a)}\right)^{\frac{1}{s}}+\left(\frac{x-a}{2(b-a)}\right)^{\frac{1}{s}}(a+b)\right]g(x)dx \\
&= \int_a^b f\left\{\left(\frac{1}{2}\right)^{\frac{1}{s}}\left[\left(\frac{b-x}{b-a}\right)^{\frac{1}{s}}a+\left(\frac{x-a}{b-a}\right)^{\frac{1}{s}}b\right]\right. \\
&\qquad \left.+\left(\frac{1}{2}\right)^{\frac{1}{s}}\left[\left(\frac{x-a}{b-a}\right)^{\frac{1}{s}}a+\left(\frac{b-x}{b-a}\right)^{\frac{1}{s}}b\right]\right\}g(x)dx \\
&\le \int_a^b \left\{\frac{1}{2}f\left[\left(\frac{b-x}{b-a}\right)^{\frac{1}{s}}a+\left(\frac{x-a}{b-a}\right)^{\frac{1}{s}}b\right]\right. \\
&\qquad \left.+\frac{1}{2}f\left[\left(\frac{x-a}{b-a}\right)^{\frac{1}{s}}a+\left(\frac{b-x}{b-a}\right)^{\frac{1}{s}}b\right]\right\}g(x)dx \\
&= \frac{1}{2}\int_a^b f\left[\left(\frac{b-x}{b-a}\right)^{\frac{1}{s}}a+\left(\frac{x-a}{b-a}\right)^{\frac{1}{s}}b\right]g(x)dx \\
&\qquad +\frac{1}{2}\int_a^b f\left[\left(\frac{x-a}{b-a}\right)^{\frac{1}{s}}a+\left(\frac{b-x}{b-a}\right)^{\frac{1}{s}}b\right]g(a+b-x)dx \\
(2.20)\qquad &= \int_a^b f\left[\left(\frac{b-x}{b-a}\right)^{\frac{1}{s}}a+\left(\frac{x-a}{b-a}\right)^{\frac{1}{s}}b\right]g(x)dx.
\end{aligned}
$$

On the other hand, using (1.7), we have

$$
\begin{aligned}
(2.21)\qquad & \int_a^b \left\{\frac{1}{2}f\left[\left(\frac{b-x}{b-a}\right)^{\frac{1}{s}}a+\left(\frac{x-a}{b-a}\right)^{\frac{1}{s}}b\right]\right. \\
&\qquad \left.+\frac{1}{2}f\left[\left(\frac{x-a}{b-a}\right)^{\frac{1}{s}}a+\left(\frac{b-x}{b-a}\right)^{\frac{1}{s}}b\right]\right\}g(x)dx
\end{aligned}
$$

$$\leq \frac{1}{2}\int_a^b \left[\frac{b-x}{b-a}f(a)+\frac{x-a}{b-a}f(b)\right]g(x)dx$$
$$+\frac{1}{2}\int_a^b \left[\frac{x-a}{b-a}f(a)+\frac{b-x}{b-a}f(b)\right]g(x)dx$$
$$=\frac{f(a)+f(b)}{2}\int_a^b g(x)dx.$$

The inequalities (2.18) follow from (2.19), (2.20) and (2.21). ∎

REMARK 9. If we choose $g(x) \equiv 1$ then Theorem 11 reduces to Theorem 5.

REMARK 10. If $s = 1$ then the inequality (2.17) reduces to the first inequality of (1.2) when $0 \leq a < b < \infty$.

THEOREM 12. *Let f, a and b be defined as in Theorem 6. Then*

$$2^{s-1}f\left(\frac{a+b}{2}\right)\int_a^b g(x)dx \tag{2.22}$$
$$\leq \int_a^b f(x)g(x)dx$$
$$\leq \frac{f(a)+f(b)}{2}\int_a^b \left[\left(\frac{b-x}{b-a}\right)^s+\left(\frac{x-a}{b-a}\right)^s\right]g(x)dx.$$

Proof. Since $f \in K_s^2$, g is nonnegative, integrable and symmetric about $\frac{a+b}{2}$, we have

$$2^{s-1}f\left(\frac{a+b}{2}\right)\int_a^b g(x)dx \tag{2.23}$$
$$=2^{s-1}\int_a^b f\left(\frac{x}{2}+\frac{a+b-x}{2}\right)g(x)dx$$
$$\leq 2^{s-1}\int_a^b \left[\left(\frac{1}{2}\right)^s f(x)+\left(\frac{1}{2}\right)^s f(a+b-x)\right]g(x)dx$$
$$=\frac{1}{2}\int_a^b [f(x)+f(a+b-x)]g(x)dx$$

$$= \frac{1}{2}\left[\int_a^b f(x)g(x)dx + \int_a^b f(a+b-x)g(a+b-x)dx\right]$$

$$= \int_a^b f(x)g(x)dx.$$

On the other hand, using (1.7) we have

$$\frac{1}{2}\left[\int_a^b [f(x)+f(a+b-x)]g(x)dx\right] \tag{2.24}$$

$$= \frac{1}{2}\int_a^b \left[f\left(\frac{b-x}{b-a}a + \frac{x-a}{b-a}b\right) + f\left(\frac{x-a}{b-a}a + \frac{b-x}{b-a}b\right)\right] g(x)dx$$

$$\leq \frac{1}{2}\int_a^b \left[\left(\frac{b-x}{b-a}\right)^s f(a) + \left(\frac{x-a}{b-a}\right)^s f(b)\right.$$

$$\left. + \left(\frac{x-a}{b-a}\right)^s f(a) + \left(\frac{b-x}{b-a}\right)^s f(b)\right] g(x)dx$$

$$= \frac{f(a)+f(b)}{2}\int_a^b \left[\left(\frac{b-x}{b-a}\right)^s + \left(\frac{x-a}{b-a}\right)^s\right] g(x)dx.$$

The inequalities (2.22) follow from (2.23) and (2.24). ∎

REMARK 11. If we choose $g(x) \equiv 1$, then Theorem 12 reduces to Theorem 6.

REMARK 12. If $s = 1$, then the inequalities (2.22) reduce to the inequalities (1.2), when $0 \leq a < b < \infty$.

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