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EXTENSION OF THE REFINED JENSEN'S OPERATOR INEQUALITY WITH CONDITION ON SPECTRA

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ABSTRACT. We give an extension of the refined Jensen's operator inequality for $n-$tuples of self-adjoint operators, unital $n-$tuples of positive linear mappings and real valued continuous convex functions with conditions on the spectra of the operators. We also study the order among quasi-arithmetic means under similar conditions.

1. Introduction

We recall some notations and definitions. Let $\mathcal{B}(H)$ be the C^*-algebra of all bounded linear operators on a Hilbert space H and 1_H stands for the identity operator. We define bounds of a self-adjoint operator $A \in \mathcal{B}(H)$ by

$$m_A = \inf_{\|x\|=1} \langle Ax, x\rangle \quad \text{and} \quad M_A = \sup_{\|x\|=1} \langle Ax, x\rangle$$

for $x \in H$. If $\mathsf{Sp}(A)$ denotes the spectrum of A, then $\mathsf{Sp}(A)$ is real and $\mathsf{Sp}(A) \subseteq [m_A, M_A]$.

For an operator $A \in \mathcal{B}(H)$ we define operators $|A|$, A^+, A^- by

$$|A| = (A^*A)^{1/2}, \qquad A^+ = (|A| + A)/2, \qquad A^- = (|A| - A)/2.$$

Obviously, if A is self-adjoint, then $|A| = (A^2)^{1/2}$ and $A^+, A^- \geq 0$ (called positive and negative parts of $A = A^+ - A^-$).

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B. Mond and J. Pečarić in [9] proved Jensen's operator inequality

$$f\left(\sum_{i=1}^{n} w_i\Phi_i(A_i)\right) \le \sum_{i=1}^{n} w_i\Phi_i\left(f(A_i)\right), \tag{1.1}$$

for operator convex functions f defined on an interval I, where $\Phi_i : \mathcal{B}(H) \to \mathcal{B}(K)$, $i = 1,\dots,n$, are unital positive linear mappings, $A_1,\dots,A_n$ are self-adjoint operators with the spectra in I and $w_1,\dots,w_n$ are non-negative real numbers with $\sum_{i=1}^n w_i = 1$.

F. Hansen, J. Pečarić and I. Perić gave in [3] a generalization of (1.1) for a unital field of positive linear mappings. The following discrete version of their inequality holds

$$f\left(\sum_{i=1}^{n} \Phi_i(A_i)\right) \le \sum_{i=1}^{n} \Phi_i\left(f(A_i)\right), \tag{1.2}$$

for operator convex functions f defined on an interval I, where $\Phi_i : \mathcal{B}(H) \to \mathcal{B}(K)$, $i = 1,\dots,n$, is a unital field of positive linear mappings (i.e. $\sum_{i=1}^n \Phi_i(1_H) = 1_K$), $A_1,\dots,A_n$ are self-adjoint operators with the spectra in I.

Recently, J. Mićić, Z. Pavić and J. Pečarić proved in [5, Theorem 1] that (1.2) stands without operator convexity of $f : I \to \mathbb{R}$ if a condition on spectra

$$(m_A, M_A) \cap [m_i, M_i] = \emptyset \quad \text{for } i = 1,\dots,n$$

holds, where m_i and M_i, $m_i \le M_i$ are bounds of A_i, $i = 1,\dots,n$; and m_A and M_A, $m_A \le M_A$, are bounds of $A = \sum_{i=1}^n \Phi_i(A_i)$ (provided that the interval I contains all m_i, M_i).

Next, they considered in [6, Theorem 2.1] the case when $(m_A, M_A) \cap [m_i, M_i] = \emptyset$ is valid for several $i \in \{1,\dots,n\}$, but not for all $i = 1,\dots,n$ and obtain an extension of (1.2) as follows.

Theorem A. Let $(A_1,\dots,A_n)$ be an $n-$tuple of self-adjoint operators $A_i \in B(H)$ with the bounds m_i and M_i, $m_i \le M_i$, $i = 1,\dots,n$. Let $(\Phi_1,\dots,\Phi_n)$ be an $n-$tuple of positive linear mappings $\Phi_i : B(H) \to B(K)$, such that $\sum_{i=1}^{n_1} \Phi_i(1_H) = \alpha\, 1_K$, $\sum_{i=n_1+1}^{n} \Phi_i(1_H) = \beta\, 1_K$, where $1 \le n_1 < n$, $\alpha,\beta > 0$ and $\alpha+\beta = 1$. Let $m = \min\{m_1,\dots,m_{n_1}\}$ and $M = \max\{M_1,\dots,M_{n_1}\}$. If

$$(m, M) \cap [m_i, M_i] = \emptyset \qquad \text{for} \quad i = n_1+1,\dots,n,$$

and one of two equalities

$$\frac{1}{\alpha}\sum_{i=1}^{n_1} \Phi_i(A_i) = \sum_{i=1}^{n} \Phi_i(A_i) = \frac{1}{\beta}\sum_{i=n_1+1}^{n} \Phi_i(A_i)$$

is valid, then

$$\frac{1}{\alpha}\sum_{i=1}^{n_1} \Phi_i(f(A_i)) \le \sum_{i=1}^{n} \Phi_i(f(A_i)) \le \frac{1}{\beta}\sum_{i=n_1+1}^{n} \Phi_i(f(A_i)), \tag{1.3}$$

holds for every continuous convex function $f : I \to \mathbb{R}$ provided that the interval I contains all m_i, M_i, $i = 1,\dots,n,$.

If $f : I \to \mathbb{R}$ is concave, then the reverse inequality is valid in (1.3).

Very recently, J. Mićić, J. Pečarić and J. Perić gave in [7, Theorem 3] the following refinement of (1.2) with condition on spectra, i.e. a refinement of [5, Theorem 3] (see also [5, Corollary 5]).

Theorem B. Let $(A_1,\ldots,A_n)$ be an $n-$tuple of self-adjoint operators $A_i\in B(H)$ with the bounds m_i and M_i, $m_i\le M_i$, $i=1,\ldots,n$. Let $(\Phi_1,\ldots,\Phi_n)$ be an $n-$tuple of positive linear mappings $\Phi_i: B(H)\to B(K)$, $i=1,\ldots,n$, such that $\sum_{i=1}^n\Phi_i(1_H)=1_K$. Let

$$(m_A,M_A)\cap[m_i,M_i]=\emptyset \quad \text{for } i=1,\ldots,n, \qquad \text{and} \qquad m<M,$$

where m_A and M_A, $m_A\le M_A$, are the bounds of the operator $A=\sum_{i=1}^n\Phi_i(A_i)$ and

$$m=\max\{M_i\colon M_i\le m_A, i\in\{1,\ldots,n\}\},\ M=\min\{m_i\colon m_i\ge M_A, i\in\{1,\ldots,n\}\}.$$

If $f: I\to\mathbb{R}$ is a continuous convex (resp. concave) function provided that the interval I contains all m_i, M_i, then

$$f\left(\sum_{i=1}^n\Phi_i(A_i)\right)\le\sum_{i=1}^n\Phi_i\left(f(A_i)\right)-\delta_f\widetilde{A}\le\sum_{i=1}^n\Phi_i\left(f(A_i)\right) \tag{1.4}$$

$$\left(\text{resp.}\quad f\left(\sum_{i=1}^n\Phi_i(A_i)\right)\ge\sum_{i=1}^n\Phi_i\left(f(A_i)\right)+\delta_f\widetilde{A}\ge\sum_{i=1}^n\Phi_i\left(f(A_i)\right)\ \right)$$

holds, where

$$\begin{aligned}
\delta_f\equiv\delta_f(\bar{m},\bar{M}) &= f(\bar{m})+f(\bar{M})-2f\left(\tfrac{\bar{m}+\bar{M}}{2}\right)\\
(\text{resp.}\quad \delta_f\equiv\delta_f(\bar{m},\bar{M}) &= 2f\left(\tfrac{\bar{m}+\bar{M}}{2}\right)-f(\bar{m})-f(\bar{M})\ ),\\
\widetilde{A}\equiv\widetilde{A}_A(\bar{m},\bar{M}) &= \tfrac{1}{2}1_K-\tfrac{1}{\bar{M}-\bar{m}}\left|A-\tfrac{\bar{m}+\bar{M}}{2}1_K\right|
\end{aligned}$$

and $\quad\bar{m}\in[m,m_A]$, $\bar{M}\in[M_A,M]$, $\bar{m}<\bar{M}$, $\quad$ are arbitrary numbers.

There is an extensive literature devoted to Jensens inequality concerning different refinements and extensive results, see, for example [1, 2, 4], [10]–[14].

In this paper we study an extension of Jensen's inequality given in Theorem B and a refinement of Theorem A. As an application of this result to the quasi-arithmetic mean with a weight, we give an extension of results given in [7] and a refinement of ones given in [6].

2. Main results

To obtain our main result we need a result [7, Lemma 2] given in the following lemma.

Lemma C. Let A be a self-adjoint operator $A\in B(H)$ with $\mathsf{Sp}(A)\subseteq[m,M]$, for some scalars $m<M$. Then

$$\begin{aligned}
f(A) &\le \frac{M1_H-A}{M-m}f(m)+\frac{A-m1_H}{M-m}f(M)-\delta_f\widetilde{A} \qquad (2.1)\\
(\text{resp.}\quad f(A) &\ge \frac{M1_H-A}{M-m}f(m)+\frac{A-m1_H}{M-m}f(M)+\delta_f\widetilde{A}\ )
\end{aligned}$$

holds for every continuous convex (resp. concave) function $f : [m, M] \to \mathbb{R}$, where

$$\delta_f = f(m) + f(M) - 2f\left(\tfrac{m+M}{2}\right) \quad (\text{resp. } \delta_f = 2f\left(\tfrac{m+M}{2}\right) - f(m) - f(M)),$$
$$\text{and} \quad \widetilde{A} = \tfrac{1}{2}1_H - \tfrac{1}{M-m}\left|A - \tfrac{m+M}{2}1_H\right|.$$

We shall give the proof for the convenience of the reader.

Proof of Lemma C. We prove only the convex case.

In [8, Theorem 1, p. 717] is prove that

$$\begin{aligned} & \min\{p_1, p_2\}\left[f(x) + f(y) - 2f\left(\tfrac{x+y}{2}\right)\right] \\ \leq\ & p_1 f(x) + p_2 f(y) - f(p_1 x + p_2 y) \end{aligned} \tag{2.2}$$

holds for every convex function f on an interval I and $x, y \in I$, $p_1, p_2 \in [0, 1]$ such that $p_1 + p_2 = 1$.

Putting $x = m, y = M$ in (2.2) it follows that

$$\begin{aligned} f(p_1 m + p_2 M) \ \leq\ & p_1 f(m) + p_2 f(M) \\ -\ & \min\{p_1, p_2\}\left(f(m) + f(M) - 2f\left(\tfrac{m+M}{2}\right)\right) \end{aligned} \tag{2.3}$$

holds for every $p_1, p_2 \in [0, 1]$ such that $p_1 + p_2 = 1$. For any $t \in [m, M]$ we can write

$$f(t) = f\left(\frac{M-t}{M-m}m + \frac{t-m}{M-m}M\right).$$

Then by using (2.3) for $p_1 = \frac{M-t}{M-m}$ and $p_2 = \frac{t-m}{M-m}$ we get

$$\begin{aligned} f(t) \ \leq\ & \frac{M-t}{M-m}f(m) + \frac{t-m}{M-m}f(M) \\ -\ & \left(\frac{1}{2} - \frac{1}{M-m}\left|t - \frac{m+M}{2}\right|\right)\left(f(m) + f(M) - 2f\left(\frac{m+M}{2}\right)\right), \end{aligned} \tag{2.4}$$

since

$$\min\left\{\frac{M-t}{M-m}, \frac{t-m}{M-m}\right\} = \frac{1}{2} - \frac{1}{M-m}\left|t - \frac{m+M}{2}\right|.$$

Finally we use the continuous functional calculus for a self-adjoint operator A: $f, g \in \mathcal{C}(I), Sp(A) \subseteq I$ and $f \geq g$ implies $f(A) \geq g(A)$; and $h(t) = |t|$ implies $h(A) = |A|$. Then by using (2.4) we obtain the desired inequality (2.1). □

In the following theorem we give an extension of Jensen's inequality given in Theorem B and a refinement of Theorem A.

Theorem 2.1. *Let $(A_1, \ldots, A_n)$ be an $n-$tuple of self-adjoint operators $A_i \in B(H)$ with the bounds m_i and M_i, $m_i \leq M_i$, $i = 1, \ldots, n$. Let $(\Phi_1, \ldots, \Phi_n)$ be an $n-$tuple of positive linear mappings $\Phi_i : B(H) \to B(K)$, such that $\sum_{i=1}^{n_1} \Phi_i(1_H) = \alpha\, 1_K$, $\sum_{i=n_1+1}^{n} \Phi_i(1_H) = \beta\, 1_K$, where $1 \leq n_1 < n$, $\alpha, \beta > 0$ and $\alpha + \beta = 1$. Let $m_L = \min\{m_1, \ldots, m_{n_1}\}$, $M_R = \max\{M_1, \ldots, M_{n_1}\}$ and*

$$m = \begin{cases} m_L, & \text{if } \{M_i\colon M_i \leq m_L, i \in \{n_1+1, \ldots, n\}\} = \emptyset, \\ \max\{M_i\colon M_i \leq m_L, i \in \{n_1+1, \ldots, n\}\}, & \text{otherwise}, \end{cases}$$
$$M = \begin{cases} M_R, & \text{if } \{m_i\colon m_i \geq M_R, i \in \{n_1+1, \ldots, n\}\} = \emptyset, \\ \min\{m_i\colon m_i \geq M_R, i \in \{n_1+1, \ldots, n\}\}, & \text{otherwise}. \end{cases}$$

If

$$(m_L, M_R) \cap [m_i, M_i] = \emptyset \quad \textit{for} \quad i = n_1+1, \ldots, n, \qquad m < M,$$

and one of two equalities

$$\frac{1}{\alpha}\sum_{i=1}^{n_1} \Phi_i(A_i) = \sum_{i=1}^{n} \Phi_i(A_i) = \frac{1}{\beta}\sum_{i=n_1+1}^{n} \Phi_i(A_i)$$

is valid, then

$$\begin{aligned}\frac{1}{\alpha}\sum_{i=1}^{n_1} \Phi_i(f(A_i)) &\le \frac{1}{\alpha}\sum_{i=1}^{n_1} \Phi_i(f(A_i)) + \beta\delta_f \widetilde{A} \le \sum_{i=1}^{n} \Phi_i(f(A_i)) \\ &\le \frac{1}{\beta}\sum_{i=n_1+1}^{n} \Phi_i(f(A_i)) - \alpha\delta_f \widetilde{A} \le \frac{1}{\beta}\sum_{i=n_1+1}^{n} \Phi_i(f(A_i)), \quad (2.5)\end{aligned}$$

holds for every continuous convex function $f : I \to \mathbb{R}$ *provided that the interval* I *contains all* m_i, M_i, $i = 1, \ldots, n$, *where*

$$\begin{aligned}\delta_f &\equiv \delta_f(\bar{m}, \bar{M}) = f(\bar{m}) + f(\bar{M}) - 2f\left(\frac{\bar{m}+\bar{M}}{2}\right) \\ \widetilde{A} &\equiv \widetilde{A}_{A,\Phi,n_1,\alpha}(\bar{m}, \bar{M}) = \frac{1}{2}1_K - \frac{1}{\alpha(\bar{M}-\bar{m})}\sum_{i=1}^{n_1} \Phi_i\left(\left|A_i - \frac{\bar{m}+\bar{M}}{2}1_H\right|\right)\end{aligned} \quad (2.6)$$

and $\bar{m} \in [m, m_L]$, $\bar{M} \in [M_R, M]$, $\bar{m} < \bar{M}$, *are arbitrary numbers.*

If $f : I \to \mathbb{R}$ *is concave, then the reverse inequality is valid in* (2.5).

Proof. We prove only the convex case.

Let us denote

$$A = \frac{1}{\alpha}\sum_{i=1}^{n_1} \Phi_i(A_i), \qquad B = \frac{1}{\beta}\sum_{i=n_1+1}^{n} \Phi_i(A_i), \qquad C = \sum_{i=1}^{n} \Phi_i(A_i).$$

It is easy to verify that $A = B$ or $B = C$ or $A = C$ implies $A = B = C$.

Since f is convex on $[\bar{m}, \bar{M}]$ and $\mathsf{Sp}(A_i) \subseteq [m_i, M_i] \subseteq [\bar{m}, \bar{M}]$ for $i = 1, \ldots, n_1$, it follows from Lemma C that

$$f(A_i) \le \frac{\bar{M}1_H - A_i}{\bar{M}-\bar{m}} f(\bar{m}) + \frac{A_i - \bar{m}1_H}{\bar{M}-\bar{m}} f(\bar{M}) - \delta_f \widetilde{A}_i, \qquad i = 1, \ldots, n_1$$

holds, where $\delta_f = f(\bar{m}) + f(\bar{M}) - 2f\left(\frac{\bar{m}+\bar{M}}{2}\right)$ and $\widetilde{A}_i = \frac{1}{2}1_H - \frac{1}{\bar{M}-\bar{m}}\left|A_i - \frac{\bar{m}+\bar{M}}{2}1_H\right|$. Applying a positive linear mapping Φ_i and summing, we obtain

$$\begin{aligned}\sum_{i=1}^{n_1} \Phi_i(f(A_i)) &\le \tfrac{\bar{M}\alpha 1_K - \sum_{i=1}^{n_1}\Phi_i(A_i)}{\bar{M}-\bar{m}} f(\bar{m}) + \tfrac{\sum_{i=1}^{n_1}\Phi_i(A_i) - \bar{m}\alpha 1_K}{\bar{M}-\bar{m}} f(\bar{M}) \\ &- \delta_f\left(\tfrac{\alpha}{2}1_K - \tfrac{1}{\bar{M}-\bar{m}}\sum_{i=1}^{n_1}\Phi_i\left(\left|A_i - \tfrac{\bar{m}+\bar{M}}{2}1_H\right|\right)\right),\end{aligned}$$

since $\sum_{i=1}^{n_1}\Phi_i(1_H) = \alpha 1_K$. It follows that

$$\frac{1}{\alpha}\sum_{i=1}^{n_1} \Phi_i(f(A_i)) \le \frac{\bar{M}1_K - A}{\bar{M}-\bar{m}} f(\bar{m}) + \frac{A - \bar{m}1_K}{\bar{M}-\bar{m}} f(\bar{M}) - \delta_f \widetilde{A}, \qquad (2.7)$$

where $\widetilde{A}=\frac{1}{2}1_K-\frac{1}{\alpha(\bar{M}-\bar{m})}\sum_{i=1}^{n_1}\Phi_i\left(\left|A_i-\frac{\bar{m}+\bar{M}}{2}1_H\right|\right)$.

In addition, since f is convex on all $[m_i,M_i]$ and $(\bar{m},\bar{M})\cap[m_i,M_i]=\emptyset$ for $i=n_1+1,\dots,n$, then

$$f(A_i)\geq\frac{\bar{M}1_H-A_i}{\bar{M}-\bar{m}}f(\bar{m})+\frac{A_i-\bar{m}1_H}{\bar{M}-\bar{m}}f(\bar{M}),\qquad i=n_1+1,\dots,n.$$

It follows

$$\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i\left(f(A_i)\right)-\delta_f\widetilde{A}\geq\frac{\bar{M}1_K-B}{\bar{M}-\bar{m}}f(\bar{m})+\frac{B-\bar{m}1_K}{\bar{M}-\bar{m}}f(\bar{M})-\delta_f\widetilde{A}.\tag{2.8}$$

Combining (2.7) and (2.8) and taking into account that $A=B$, we obtain

$$\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i\left(f(A_i)\right)\leq\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i\left(f(A_i)\right)-\delta_f\widetilde{A}.\tag{2.9}$$

Next, we obtain

$$\begin{aligned}
&\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i))\\
=\;&\sum_{i=1}^{n_1}\Phi_i(f(A_i))+\frac{\beta}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i))\quad(\text{by }\alpha+\beta=1)\\
\leq\;&\sum_{i=1}^{n_1}\Phi_i(f(A_i))+\sum_{i=n_1+1}^{n}\Phi_i(f(A_i))-\beta\delta_f\widetilde{A}\qquad(\text{by }(2.9))\\
\leq\;&\frac{\alpha}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i))-\alpha\delta_f\widetilde{A}+\sum_{i=n_1+1}^{n}\Phi_i(f(A_i))-\beta\delta_f\widetilde{A}\qquad(\text{by }(2.9))\\
=\;&\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i))-\delta_f\widetilde{A}\quad(\text{by }\alpha+\beta=1),
\end{aligned}$$

which gives the following double inequality

$$\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i))\leq\sum_{i=1}^{n}\Phi_i(f(A_i))-\beta\delta_f\widetilde{A}\leq\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i))-\delta_f\widetilde{A}.$$

Adding $\beta\delta_f\widetilde{A}$ in the above inequalities, we get

$$\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i))+\beta\delta_f\widetilde{A}\leq\sum_{i=1}^{n}\Phi_i(f(A_i))\leq\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i))-\alpha\delta_f\widetilde{A}.\tag{2.10}$$

Now, we remark that $\delta_f\geq 0$ and $\widetilde{A}\geq 0$. (Indeed, since f is convex, then $f\left((\bar{m}+\bar{M})/2\right)\leq(f(\bar{m})+f(\bar{M}))/2$, which implies that $\delta_f\geq 0$. Also, since

$$\mathsf{Sp}(A_i)\subseteq[\bar{m},\bar{M}]\quad\Rightarrow\quad\left|A_i-\frac{\bar{M}+\bar{m}}{2}1_H\right|\leq\frac{\bar{M}-\bar{m}}{2}1_H,\qquad\text{for }i=1,\dots,n_1,$$

then

$$\sum_{i=1}^{n_1} \Phi_i \left(\left| A_i - \frac{\bar{M}+\bar{m}}{2} 1_H \right| \right) \le \frac{\bar{M}-\bar{m}}{2} \alpha 1_K,$$

which gives

$$0 \le \frac{1}{2} 1_K - \frac{1}{\alpha(\bar{M}-\bar{m})} \sum_{i=1}^{n_1} \Phi_i \left(\left| A_i - \frac{\bar{M}+\bar{m}}{2} 1_H \right| \right) = \widetilde{A}. \qquad)$$

Consequently, the following inequalities

$$\frac{1}{\alpha} \sum_{i=1}^{n_1} \Phi_i(f(A_i)) \le \frac{1}{\alpha} \sum_{i=1}^{n_1} \Phi_i(f(A_i)) + \beta \delta_f \widetilde{A},$$

$$\frac{1}{\beta} \sum_{i=n_1+1}^{n} \Phi_i(f(A_i)) - \alpha \delta_f \widetilde{A} \le \frac{1}{\beta} \sum_{i=n_1+1}^{n} \Phi_i(f(A_i)),$$

hold, which with (2.10) proves the desired series inequalities (2.5).

□

Example 2.2. We observe the matrix case of Theorem 2.1 for $f(t) = t^4$, which is the convex function but not operator convex, $n = 4$, $n_1 = 2$ and the bounds of matrices as in Figure 1.

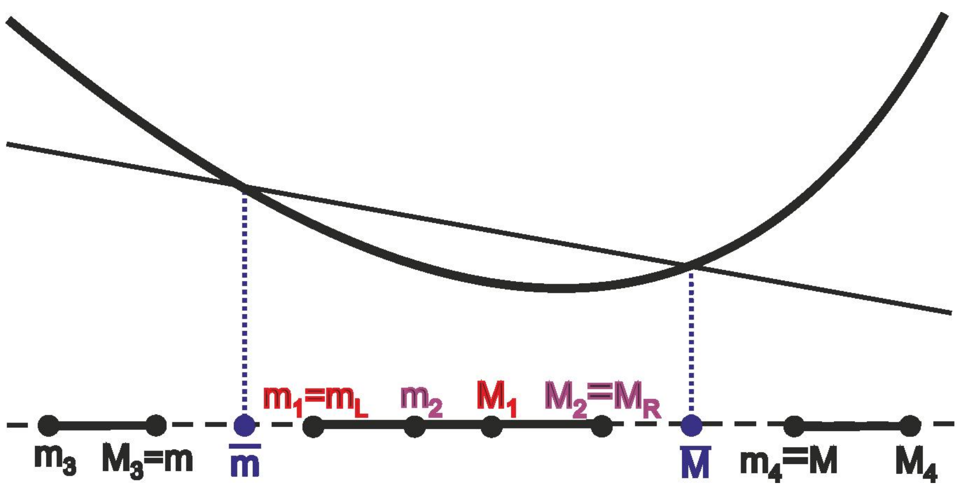

FIGURE 1. An example a convex function and the bounds of four operators

We show an example such that

$$\begin{aligned} \tfrac{1}{\alpha}\left(\Phi_1(A_1^4)+\Phi_2(A_2^4)\right) &< \tfrac{1}{\alpha}\left(\Phi_1(A_1^4)+\Phi_2(A_2^4)\right) + \beta\delta_f \widetilde{A} \\ &< \Phi_1(A_1^4)+\Phi_2(A_2^4)+\Phi_3(A_3^4)+\Phi_4(A_4^4) \\ &< \tfrac{1}{\beta}\left(\Phi_3(A_3^4)+\Phi_4(A_4^4)\right) - \alpha\delta_f \widetilde{A} < \tfrac{1}{\beta}\left(\Phi_3(A_3^4)+\Phi_4(A_4^4)\right) \end{aligned} \tag{2.11}$$

holds, where $\delta_f = \bar{M}^4 + \bar{m}^4 - (\bar{M}+\bar{m})^4/8$ and

$$\widetilde{A} = \frac{1}{2} I_2 - \frac{1}{\alpha(\bar{M}-\bar{m})} \left(\Phi_1 \left(|A_1 - \frac{\bar{M}+\bar{m}}{2} I_h| \right) + \Phi_2 \left(|A_2 - \frac{\bar{M}+\bar{m}}{2} I_3| \right) \right).$$

We define mappings $\Phi_i : M_3(\mathbb{C}) \to M_2(\mathbb{C})$ as follows: $\Phi_i((a_{jk})_{1\le j,k\le 3}) = \frac{1}{4}(a_{jk})_{1\le j,k\le 2}$, $i = 1,\dots,4$. Then $\sum_{i=1}^{4} \Phi_i(I_3) = I_2$ and $\alpha = \beta = \frac{1}{2}$.
Let

$$A_1 = 2\begin{pmatrix} 2 & 9/8 & 1 \\ 9/8 & 2 & 0 \\ 1 & 0 & 3 \end{pmatrix}, \qquad A_2 = 3\begin{pmatrix} 2 & 9/8 & 0 \\ 9/8 & 1 & 0 \\ 0 & 0 & 2 \end{pmatrix},$$

$$A_3 = -3\begin{pmatrix} 4 & 1/2 & 1 \\ 1/2 & 4 & 0 \\ 1 & 0 & 2 \end{pmatrix}, \qquad A_4 = 12\begin{pmatrix} 5/3 & 1/2 & 0 \\ 1/2 & 3/2 & 0 \\ 0 & 0 & 3 \end{pmatrix}.$$

Then $m_1 = 1.28607$, $M_1 = 7.70771$, $m_2 = 0.53777$, $M_2 = 5.46221$, $m_3 = -14.15050$, $M_3 = -4.71071$, $m_4 = 12.91724$, $M_4 = 36.$, so $m_L = m_2$, $M_R = M_1$, $m = M_3$ and $M = m_4$ (rounded to five decimal places). Also,

$$\frac{1}{\alpha}\left(\Phi_1(A_1) + \Phi_2(A_2)\right) = \frac{1}{\beta}\left(\Phi_3(A_3) + \Phi_4(A_4)\right) = \begin{pmatrix} 4 & 9/4 \\ 9/4 & 3 \end{pmatrix},$$

and

$$\begin{aligned} A_f \equiv \frac{1}{\alpha}\left(\Phi_1(A_1^4) + \Phi_2(A_2^4)\right) &= \begin{pmatrix} 989.00391 & 663.46875 \\ 663.46875 & 526.12891 \end{pmatrix}, \\ C_f \equiv \Phi_1(A_1^4) + \Phi_2(A_2^4) + \Phi_3(A_3^4) + \Phi_4(A_4^4) &= \begin{pmatrix} 68093.14258 & 48477.98437 \\ 48477.98437 & 51335.39258 \end{pmatrix}, \\ B_f \equiv \frac{1}{\beta}\left(\Phi_3(A_3^4) + \Phi_4(A_4^4)\right) &= \begin{pmatrix} 135197.28125 & 96292.5 \\ 96292.5 & 102144.65625 \end{pmatrix}. \end{aligned}$$

Then

$$A_f < C_f < B_f \tag{2.12}$$

holds (which is consistent with (1.3)).

We will choose three pairs of numbers $(\bar{m}, \bar{M})$, $\bar{m} \in [-4.71071, 0.53777]$, $\bar{M} \in [7.70771, 12.91724]$ as follows:

i) $\bar{m} = m_L = 0.53777$, $\bar{M} = M_R = 7.70771$, then

$$\widetilde{\Delta}_1 = \beta\delta_f\widetilde{A} = 0.5\cdot 2951.69249\cdot\begin{pmatrix} 0.15678 & 0.09030 \\ 0.09030 & 0.15943 \end{pmatrix} = \begin{pmatrix} 231.38908 & 133.26139 \\ 133.26139 & 235.29515 \end{pmatrix},$$

ii) $\bar{m} = m = -4.71071$, $\bar{M} = M = 12.91724$, then

$$\widetilde{\Delta}_2 = \beta\delta_f\widetilde{A} = 0.5\cdot 27766.07963\cdot\begin{pmatrix} 0.36022 & 0.03573 \\ 0.03573 & 0.36155 \end{pmatrix} = \begin{pmatrix} 5000.89860 & 496.04498 \\ 496.04498 & 5019.50711 \end{pmatrix},$$

iii) $\bar{m} = -1$, $\bar{M} = 10$, then

$$\widetilde{\Delta}_3 = \beta\delta_f\widetilde{A} = 0.5\cdot 9180.875\cdot\begin{pmatrix} 0.28203 & 0.08975 \\ 0.08975 & 0.27557 \end{pmatrix} = \begin{pmatrix} 1294.66 & 411.999 \\ 411.999 & 1265. \end{pmatrix}.$$

New, we obtain the following improvement of (2.12) (see (2.11)):

i) $$A_f < A_f + \widetilde{\Delta}_1 = \begin{pmatrix} 1220.39299 & 796.73014 \\ 796.73014 & 761.42406 \end{pmatrix}$$

$$< C_f < \begin{pmatrix} 134965.89217 & 96159.23861 \\ 96159.23861 & 101909.36110 \end{pmatrix} = B_f - \widetilde{\Delta}_1 < B_f,$$

ii) $$A_f < A_f + \widetilde{\Delta}_2 = \begin{pmatrix} 5989.90251 & 1159.51373 \\ 1159.51373 & 5545.63601 \end{pmatrix}$$
$$< C_f < \begin{pmatrix} 130196.38265 & 95796.45502 \\ 95796.45502 & 97125.14914 \end{pmatrix} = B_f - \widetilde{\Delta}_2 < B_f,$$

iii) $$A_f < A_f + \widetilde{\Delta}_3 = \begin{pmatrix} 2283.66362 & 1075.46746 \\ 1075.46746 & 1791.12874 \end{pmatrix}$$
$$< C_f < \begin{pmatrix} 133902.62153 & 95880.50129 \\ 95880.50129 & 100879.65641 \end{pmatrix} = B_f - \widetilde{\Delta}_3 < B_f.$$

Using Theorem 2.1 we get the following result.

Corollary 2.3. *Let the assumptions of Theorem 2.1 hold. Then*

$$\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i)) \le \frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i)) + \gamma_1\delta_f\widetilde{A} \le \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i)) \tag{2.13}$$

and

$$\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i)) \le \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i)) - \gamma_2\delta_f\widetilde{A} \le \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i)) \tag{2.14}$$

holds for every γ_1, γ_2 in the close interval joining α and β, where δ_f and $\widetilde{A}$ are defined by (2.6).

Proof. Adding $\alpha\delta_f\widetilde{A}$ in (2.5) and noticing $\delta_f\widetilde{A} \ge 0$, we obtain

$$\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i)) \le \frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i)) + \alpha\delta_f\widetilde{A} \le \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i)).$$

Taking into account the above inequality and the left hand side of (2.5) we obtain (2.13).

Similarly, subtracting $\beta\delta_f\widetilde{A}$ in (2.5) we obtain (2.14). □

Remark 2.4. *Let the assumptions of Theorem 2.1 be valid.*

1) We observe that the following inequality

$$f\left(\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(A_i)\right) \le \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i)) - \delta_f\widetilde{A}_\beta \le \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i)),$$

holds for every continuous convex function $f : I \to \mathbb{R}$ provided that the interval I contains all m_i, M_i, $i = 1, \dots, n$, where δ_f is defined by (2.6),

$$\widetilde{A}_\beta \equiv \widetilde{A}_{\beta,A,\Phi,n_1}(\bar{m}, \bar{M}) = \frac{1}{2}1_K - \frac{1}{\bar{M} - \bar{m}}\left|\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i A_i - \frac{\bar{m} + \bar{M}}{2}1_K\right|$$

and $\bar{m} \in [m, m_L]$, $\bar{M} \in [M_R, M]$, $\bar{m} < \bar{M}$, are arbitrary numbers.

Indeed, by the assumptions of Theorem 2.1 we have

$$m_L\alpha 1_H \leq \sum_{i=1}^{n_1}\Phi_i(A_i) \leq M_R\alpha 1_H \quad \text{and} \quad \frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(A_i) = \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(A_i)$$

which implies

$$m_L 1_H \leq \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(A_i) \leq M_R 1_H.$$

Also $(m_L, M_R)\cap[m_i, M_i] = \emptyset$ for $i = n_1+1,\ldots,n$ and $\sum_{i=n_1+1}^{n}\frac{1}{\beta}\Phi_i(1_H) = 1_K$ hold. So we can apply Theorem B on operators $A_{n_1+1},\ldots,A_n$ and mappings $\frac{1}{\beta}\Phi_i$. We obtain the desired inequality.

2) We denote by m_C and M_C the bounds of $C = \sum_{i=1}^{n}\Phi_i(A_i)$. If $(m_C, M_C)\cap [m_i, M_i] = \emptyset$, $i = 1,\ldots,n_1$, then series inequality (2.5) can be extended from the left side if we use refined Jensen's operator inequality (1.4)

$$\begin{aligned}
f\left(\sum_{i=1}^{n}\Phi_i(A_i)\right) &= f\left(\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(A_i)\right) \leq \frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i)) - \delta_f\widetilde{A}_\alpha \\
\leq\ & \frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i)) \leq \frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i)) + \beta\delta_f\widetilde{A} \leq \sum_{i=1}^{n}\Phi_i(f(A_i)) \\
\leq\ & \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i)) - \alpha\delta_f\widetilde{A} \leq \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i)),
\end{aligned}$$

where δ_f and $\widetilde{A}$ are defined by (2.6),

$$\widetilde{A}_\alpha \equiv \widetilde{A}_{\alpha,A,\Phi,n_1}(\bar{m},\bar{M}) = \frac{1}{2}1_K - \frac{1}{\bar{M}-\bar{m}}\left|\frac{1}{\alpha}\sum_{i=n_1+1}^{n}\Phi_i A_i - \frac{\bar{m}+\bar{M}}{2}1_K\right|$$

Remark 2.5. We obtain the equivalent inequalities to the ones in Theorem 2.1 in the case when $\sum_{i=1}^{n}\Phi_i(1_H) = \gamma\, 1_K$, for some positive scalar γ. If $\alpha+\beta = \gamma$ and one of two equalities

$$\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(A_i) = \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(A_i) = \frac{1}{\gamma}\sum_{i=1}^{n}\Phi_i(A_i)$$

is valid, then

$$\begin{aligned}
\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i)) &\leq \frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i)) + \frac{\beta}{\gamma}\delta_f\widetilde{A} \leq \frac{1}{\gamma}\sum_{i=1}^{n}\Phi_i(f(A_i)) \\
&\leq \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i)) - \frac{\alpha}{\gamma}\delta_f\widetilde{A} \leq \frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(f(A_i)),
\end{aligned}$$

holds for every continuous convex function $f: I \to \mathbb{R}$ provided that the interval I contains all m_i, M_i, $i = 1,\ldots,n$, where δ_f and $\widetilde{A}$ are defined by (2.6).

With respect to Remark 2.5, we obtain the following obvious corollary of Theorem 2.1 with the convex combination of operators A_i, $i = 1,\ldots,n$.

Corollary 2.6. *Let $(A_1,\dots,A_n)$ be an $n-$tuple of self-adjoint operators $A_i \in B(H)$ with the bounds m_i and M_i, $m_i \le M_i$, $i=1,\dots,n$. Let $(p_1,\dots,p_n)$ be an $n-$tuple of non-negative numbers such that $0<\sum_{i=1}^{n_1} p_i = \mathbf{p_{n_1}} < \mathbf{p_n} = \sum_{i=1}^{n} p_i$, where $1 \le n_1 < n$. Let*
$m_L=\min\{m_1,\dots,m_{n_1}\}$, $M_R=\max\{M_1,\dots,M_{n_1}\}$ and

$$m = \begin{cases} m_L, & \text{if } \{M_i\colon M_i \le m_L, i\in\{n_1+1,\dots,n\}\}=\emptyset, \\ \max\{M_i\colon M_i\le m_L, i\in\{n_1+1,\dots,n\}\}, & \text{otherwise}, \end{cases}$$
$$M = \begin{cases} M_R, & \text{if } \{m_i\colon m_i \ge M_R, i\in\{n_1+1,\dots,n\}\}=\emptyset, \\ \min\{m_i\colon m_i\ge M_R, i\in\{n_1+1,\dots,n\}\}, & \text{otherwise}. \end{cases}$$

If

$$(m_L,M_R)\cap[m_i,M_i]=\emptyset \quad \text{for} \quad i=n_1+1,\dots,n, \qquad m<M,$$

and one of two equalities

$$\frac{1}{\mathbf{p_{n_1}}}\sum_{i=1}^{n_1} p_iA_i = \frac{1}{\mathbf{p_n}}\sum_{i=1}^{n} p_iA_i = \frac{1}{\mathbf{p_n}-\mathbf{p_{n_1}}}\sum_{i=n_1+1}^{n} p_iA_i$$

is valid, then

$$\begin{aligned} \frac{1}{\mathbf{p_{n_1}}}\sum_{i=1}^{n_1} p_if(A_i) &\le \frac{1}{\mathbf{p_{n_1}}}\sum_{i=1}^{n_1} p_if(A_i) + \left(1-\frac{\mathbf{p_{n_1}}}{\mathbf{p_n}}\right)\delta_f\widetilde{A} \le \frac{1}{\mathbf{p_n}}\sum_{i=1}^{n} p_if(A_i) \\ &\le \frac{1}{\mathbf{p_n}-\mathbf{p_{n_1}}}\sum_{i=n_1+1}^{n} p_if(A_i) - \frac{\mathbf{p_{n_1}}}{\mathbf{p_n}}\delta_f\widetilde{A} \le \frac{1}{\mathbf{p_n}-\mathbf{p_{n_1}}}\sum_{i=n_1+1}^{n} p_if(A_i), \end{aligned} \tag{2.15}$$

holds for every continuous convex function $f: I\to\mathbb{R}$ provided that the interval I contains all m_i, M_i, $i=1,\dots,n$, where where δ_f is defined by (2.6),

$$\widetilde{A}\equiv\widetilde{A}_{A,p,n_1}(\bar{m},\bar{M}) = \frac{1}{2}1_H - \frac{1}{\mathbf{p_{n_1}}(\bar{M}-\bar{m})}\sum_{i=1}^{n_1} p_i\left(\left|A_i-\frac{\bar{m}+\bar{M}}{2}1_H\right|\right)$$

and $\bar{m}\in[m,m_L]$, $\bar{M}\in[M_R,M]$, $\bar{m}<\bar{M}$, are arbitrary numbers.

If $f: I\to\mathbb{R}$ is concave, then the reverse inequality is valid in (2.15).

As a special case of Corollary 2.6 we obtain an extension of [7, Corollary 6].

Corollary 2.7. *Let $(A_1,\dots,A_n)$ be an $n-$tuple of self-adjoint operators $A_i \in B(H)$ with the bounds m_i and M_i, $m_i \le M_i$, $i=1,\dots,n$. Let $(p_1,\dots,p_n)$ be an $n-$tuple of non-negative numbers such that $\sum_{i=1}^{n} p_i=1$. Let*

$$(m_A,M_A)\cap[m_i,M_i]=\emptyset \quad \text{for } i=1,\dots,n, \qquad \text{and} \qquad m<M,$$

where m_A and M_A, $m_A\le M_A$, are the bounds of $A=\sum_{i=1}^{n} p_iA_i$ and

$$m=\max\{M_i\le m_A, i\in\{1,\dots,n\}\},\ M=\min\{m_i\ge M_A, i\in\{1,\dots,n\}\}.$$

If $f : I \to \mathbb{R}$ is a continuous convex function provided that the interval I contains all m_i, M_i, then

$$f(\sum_{i=1}^{n} p_i A_i) \le f(\sum_{i=1}^{n} p_i A_i) + \frac{1}{2}\delta_f \tilde{\tilde{A}} \le \frac{1}{2} f(\sum_{i=1}^{n} p_i A_i) + \frac{1}{2}\sum_{i=1}^{n} p_i f(A_i) \\ \le \sum_{i=1}^{n} p_i f(A_i) - \frac{1}{2}\delta_f \tilde{\tilde{A}} \le \sum_{i=1}^{n} p_i f(A_i), \tag{2.16}$$

holds, where δ_f is defined by (2.6), $\tilde{\tilde{A}} = \frac{1}{2}1_H - \frac{1}{\bar{M}-\bar{m}} \left| \sum_{i=1}^{n} p_i A_i - \frac{\bar{m}+\bar{M}}{2} 1_H \right|$ and $\bar{m} \in [m, m_A]$, $\bar{M} \in [M_A, M]$, $\bar{m} < \bar{M}$, are arbitrary numbers.

If $f : I \to \mathbb{R}$ is concave, then the reverse inequality is valid in (2.16).

Proof. We prove only the convex case.

We define $(n+1)-$tuple of operators $(B_1, \dots, B_{n+1})$, $B_i \in B(H)$, by $B_1 = A = \sum_{i=1}^{n} p_i A_i$ and $B_i = A_{i-1}$, $i = 2, \dots, n+1$. Then $m_{B_1} = m_A$, $M_{B_1} = M_A$ are the bounds of B_1 and $m_{B_i} = m_{i-1}$, $M_{B_i} = M_{i-1}$ are the ones of B_i, $i = 2, \dots, n+1$. Also, we define $(n+1)-$tuple of non-negative numbers $(q_1, \dots, q_{n+1})$ by $q_1 = 1$ and $q_i = p_{i-1}$, $i = 2, \dots, n+1$. We have that $\sum_{i=1}^{n+1} q_i = 2$ and

$$(m_{B_1}, M_{B_1}) \cap [m_{B_i}, M_{B_i}] = \emptyset, \quad \text{for } i = 2, \dots, n+1 \quad \text{and} \quad m < M \tag{2.17}$$

holds. Since

$$\sum_{i=1}^{n+1} q_i B_i = B_1 + \sum_{i=2}^{n+1} q_i B_i = \sum_{i=1}^{n} p_i A_i + \sum_{i=1}^{n} p_i A_i = 2B_1,$$

then

$$q_1 B_1 = \frac{1}{2}\sum_{i=1}^{n+1} q_i B_i = \sum_{i=2}^{n+1} q_i B_i. \tag{2.18}$$

Taking into account (2.17) and (2.18), we can apply Corollary 2.6 for $n_1 = 1$ and B_i, q_i as above, and we get

$$q_1 f(B_1) \le q_1 f(B_1) + \frac{1}{2}\delta_f \widetilde{B} \le \frac{1}{2}\sum_{i=1}^{n+1} q_i f(B_i) \le \sum_{i=2}^{n+1} q_i f(B_i) - \frac{1}{2}\delta_f \widetilde{B} \le \sum_{i=2}^{n+1} q_i f(B_i),$$

where $\widetilde{B} = \frac{1}{2}1_H - \frac{1}{\bar{M}-\bar{m}} \left| B_1 - \frac{\bar{m}+\bar{M}}{2} 1_H \right|$, which gives the desired inequality (2.16). □

3. Quasi-arithmetic means

In this section we study an application of Theorem 2.1 to the quasi-arithmetic mean with weight.

For a subset $\{A_{n_1}, \dots, A_{n_2}\}$ of $\{A_1, \dots, A_n\}$, we denote the quasi-arithmetic mean by

$$\mathcal{M}_\varphi(\gamma, \mathbf{A}, \mathbf{\Phi}, n_1, n_2) = \varphi^{-1}\left(\frac{1}{\gamma}\sum_{i=n_1}^{n_2} \Phi_i\left(\varphi(A_i)\right)\right), \tag{3.1}$$

where $(A_{n_1},\dots,A_{n_2})$ are self-adjoint operators in $\mathcal{B}(H)$ with the spectra in I, $(\Phi_{n_1},\dots,\Phi_{n_2})$ are positive linear mappings $\Phi_i:\mathcal{B}(H)\to\mathcal{B}(K)$ such that $\sum_{i=n_1}^{n_2}\Phi_i(1_H)=\gamma\,1_K$, and $\varphi: I\to\mathbb{R}$ is a continuous strictly monotone function.

Under the same conditions, for convenience we introduce the following denotations

$$\begin{aligned}\delta_{\varphi,\psi}(m,M) &= \psi(m)+\psi(M)-2\psi\circ\varphi^{-1}\left(\tfrac{\varphi(m)+\varphi(M)}{2}\right),\\ \widetilde{A}_{\varphi,n_1,\gamma}(m,M) &= \tfrac{1}{2}1_K-\tfrac{1}{\gamma(M-m)}\textstyle\sum_{i=1}^{n_1}\Phi_i\left(\left|\varphi(A_i)-\tfrac{\varphi(M)+\varphi(m)}{2}1_H\right|\right),\end{aligned} \tag{3.2}$$

where $\varphi,\psi: I\to\mathbb{R}$ are continuous strictly monotone functions and $m,M\in I$, $m<M$. Of course, we include implicitly that $\widetilde{A}_{\varphi,n_1,\gamma}(m,M)\equiv\widetilde{A}_{\varphi,A,\Phi,n_1,\gamma}(m,M)$.

The following theorem is an extension of [7, Theorem 7] and a refinement of [6, Theorem 3.1].

Theorem 3.1. *Let $(A_1,\dots,A_n)$ be an $n-$tuple of self-adjoint operators $A_i\in B(H)$ with the bounds m_i and M_i, $m_i\le M_i$, $i=1,\dots,n$. Let $\varphi,\psi: I\to\mathbb{R}$ be continuous strictly monotone functions on an interval I which contains all m_i,M_i. Let $(\Phi_1,\dots,\Phi_n)$ be an $n-$tuple of positive linear mappings $\Phi_i: B(H)\to B(K)$, such that $\sum_{i=1}^{n_1}\Phi_i(1_H)=\alpha\,1_K$, $\sum_{i=n_1+1}^{n}\Phi_i(1_H)=\beta\,1_K$, where $1\le n_1<n$, $\alpha,\beta>0$ and $\alpha+\beta=1$. Let one of two equalities*

$$\mathcal{M}_\varphi(\alpha,\mathbf{A},\mathbf{\Phi},1,n_1)=\mathcal{M}_\varphi(1,\mathbf{A},\mathbf{\Phi},1,n)=\mathcal{M}_\varphi(\beta,\mathbf{A},\mathbf{\Phi},n_1+1,n) \tag{3.3}$$

be valid and let

$$(m_L,M_R)\cap[m_i,M_i]=\emptyset \quad \textit{for} \quad i=n_1+1,\dots,n, \qquad m<M,$$

where $m_L=\min\{m_1,\dots,m_{n_1}\}$, $M_R=\max\{M_1,\dots,M_{n_1}\}$,

$$\begin{aligned} m &= \begin{cases} m_L, & \text{if } \{M_i\colon M_i\le m_L, i\in\{n_1+1,\dots,n\}\}=\emptyset,\\ \max\{M_i\colon M_i\le m_L, i\in\{n_1+1,\dots,n\}\}, & \text{otherwise,}\end{cases}\\ M &= \begin{cases} M_R, & \text{if } \{m_i\colon m_i\ge M_R, i\in\{n_1+1,\dots,n\}\}=\emptyset,\\ \min\{m_i\colon m_i\ge M_R, i\in\{n_1+1,\dots,n\}\}, & \text{otherwise.}\end{cases}\end{aligned}$$

(i) *If $\psi\circ\varphi^{-1}$ is convex and ψ^{-1} is operator monotone, then*

$$\begin{aligned}\mathcal{M}_\psi(\alpha,\mathbf{A},\mathbf{\Phi},1,n_1) &\le \psi^{-1}\left(\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i\left(\psi(A_i)\right)+\beta\delta_{\varphi,\psi}\widetilde{A}_{\varphi,n_1,\alpha}\right)\\ &\le \mathcal{M}_\psi(1,\mathbf{A},\mathbf{\Phi},1,n)\le\psi^{-1}\left(\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i\left(\psi(A_i)\right)-\alpha\delta_{\varphi,\psi}\widetilde{A}_{\varphi,n_1,\alpha}\right)\\ &\le \mathcal{M}_\psi(\beta,\mathbf{A},\mathbf{\Phi},n_1+1,n)\end{aligned} \tag{3.4}$$

holds, where $\delta_{\varphi,\psi}\ge 0$ and $\widetilde{A}_{\varphi,n_1,\alpha}\ge 0$.

(i′) *If $\psi\circ\varphi^{-1}$ is convex and $-\psi^{-1}$ is operator monotone, then the reverse inequality is valid in (3.4), where $\delta_{\varphi,\psi}\ge 0$ and $\widetilde{A}_{\varphi,n_1,\alpha}\ge 0$.*

(ii) *If $\psi\circ\varphi^{-1}$ is concave and $-\psi^{-1}$ is operator monotone, then (3.4) holds, where $\delta_{\varphi,\psi}\le 0$ and $\widetilde{A}_{\varphi,n_1,\alpha}\ge 0$.*

(ii′) *If $\psi \circ \varphi^{-1}$ is concave and ψ^{-1} is operator monotone, then the reverse inequality is valid in (3.4), where $\delta_{\varphi,\psi} \leq 0$ and $\widetilde{A}_{\varphi,n_1,\alpha} \geq 0$.*

In all the above cases, we assume that $\delta_{\varphi,\psi} \equiv \delta_{\varphi,\psi}(\bar{m}, \bar{M})$, $\widetilde{A}_{\varphi,n_1,\alpha} \equiv \widetilde{A}_{\varphi,n_1,\alpha}(\bar{m}, \bar{M})$ are defined by (3.2) and $\bar{m} \in [m, m_L]$, $\bar{M} \in [M_R, M]$, $\bar{m} < \bar{M}$, are arbitrary numbers.

Proof. We only prove the case (i). Suppose that φ is a strictly increasing function. Then

$$(m_L, M_R) \cap [m_i, M_i] = \emptyset \qquad \text{for} \quad i = n_1 + 1, \dots, n$$

implies

$$(\varphi(m_L), \varphi(M_R)) \cap [\varphi(m_i), \varphi(M_i)] = \emptyset \quad \text{ for } i = n_1 + 1, \dots, n. \tag{3.5}$$

Also, by using (3.3), we have

$$\frac{1}{\alpha}\sum_{i=1}^{n_1} \Phi_i\left(\varphi(A_i)\right) = \sum_{i=1}^{n} \Phi_i\left(\varphi(A_i)\right) = \frac{1}{\beta}\sum_{i=n_1+1}^{n} \Phi_i\left(\varphi(A_i)\right).$$

Taking into account (3.5) and the above double equality, we obtain by Theorem 2.1

$$\begin{aligned}\frac{1}{\alpha}\sum_{i=1}^{n_1} \Phi_i(f\left(\varphi(A_i)\right)) &\leq \frac{1}{\alpha}\sum_{i=1}^{n_1} \Phi_i(f\left(\varphi(A_i)\right)) + \beta\delta_f \widetilde{A}_{\varphi,n_1,\alpha} \leq \sum_{i=1}^{n} \Phi_i(f\left(\varphi(A_i)\right)) \\ &\leq \frac{1}{\beta}\sum_{i=n_1+1}^{n} \Phi_i(f\left(\varphi(A_i)\right)) - \alpha\delta_f \widetilde{A}_{\varphi,n_1,\alpha} \leq \frac{1}{\beta}\sum_{i=n_1+1}^{n} \Phi_i(f\left(\varphi(A_i)\right)),\end{aligned} \tag{3.6}$$

for every continuous convex function $f : J \to \mathbb{R}$ on an interval J which contains all $[\varphi(m_i), \varphi(M_i)] = \varphi([m_i, M_i])$, $i = 1, \dots, n$, where $\delta_f = f(\varphi(m)) + f(\varphi(M)) - 2f\left(\frac{\varphi(m)+\varphi(M)}{2}\right)$.

Also, if φ is strictly decreasing, then we check that (3.6) holds for convex $f : J \to \mathbb{R}$ on J which contains all $[\varphi(M_i), \varphi(m_i)] = \varphi([m_i, M_i])$.

Putting $f = \psi \circ \varphi^{-1}$ in (3.6), we obtain

$$\begin{aligned}\frac{1}{\alpha}\sum_{i=1}^{n_1} \Phi_i\left(\psi(A_i)\right) &\leq \frac{1}{\alpha}\sum_{i=1}^{n_1} \Phi_i\left(\psi(A_i)\right) + \beta\delta_{\varphi,\psi} \widetilde{A}_{\varphi,n_1,\alpha} \leq \sum_{i=1}^{n} \Phi_i\left(\psi(A_i)\right) \\ &\leq \frac{1}{\beta}\sum_{i=n_1+1}^{n} \Phi_i\left(\psi(A_i)\right) - \alpha\delta_{\varphi,\psi} \widetilde{A}_{\varphi,n_1,\alpha} \leq \frac{1}{\beta}\sum_{i=n_1+1}^{n} \Phi_i\left(\psi(A_i)\right).\end{aligned}$$

Applying an operator monotone function ψ^{-1} on the above double inequality, we obtain the desired inequality (3.4). □

We now give some particular results of interest that can be derived from Theorem 3.1, which are an extension of [7, Corollary 8, Corollary 10] and a refinement of [6, Corollary 3.3].

Corollary 3.2. *Let $(A_1,\dots,A_n)$ and $(\Phi_1,\dots,\Phi_n)$, m_i, M_i, m, M, m_L, M_R, α and β be as in Theorem 3.1. Let I be an interval which contains all m_i, M_i and*

$$(m_L, M_R)\cap[m_i,M_i]=\emptyset \quad \textit{for} \quad i=n_1+1,\dots,n, \qquad m<M.$$

I) *If one of two equalities*

$$\mathcal{M}_\varphi(\alpha,\mathbf{A},\mathbf{\Phi},1,n_1)=\mathcal{M}_\varphi(1,\mathbf{A},\mathbf{\Phi},1,n)=\mathcal{M}_\varphi(\beta,\mathbf{A},\mathbf{\Phi},n_1+1,n)$$

is valid, then

$$\begin{aligned}\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(A_i)&\le\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(A_i)+\beta\delta_{\varphi^{-1}}\widetilde{A}_{\varphi,n_1,\alpha}\le\sum_{i=1}^{n}\Phi_i(A_i)\\ &\le\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(A_i)-\alpha\delta_{\varphi^{-1}}\widetilde{A}_{\varphi,n_1,\alpha}\le\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i\Phi_i(A_i).\end{aligned} \tag{3.7}$$

holds for every continuous strictly monotone function $\varphi: I\to\mathbb{R}$ such that φ^{-1} is convex on I, where $\delta_{\varphi^{-1}}=\bar{m}+\bar{M}-2\,\varphi^{-1}\left(\frac{\varphi(\bar{m})+\varphi(\bar{M})}{2}\right)\ge 0$, $\widetilde{A}_{\varphi,n_1,\alpha}=\frac{1}{2}1_K-\frac{1}{\alpha(\bar{M}-\bar{m})}\sum_{i=1}^{n_1}\Phi_i\left(\left|\varphi(A_i)-\frac{\varphi(\bar{M})+\varphi(\bar{m})}{2}1_H\right|\right)$ and $\bar{m}\in[m,m_L]$, $\bar{M}\in[M_R,M]$, $\bar{m}<\bar{M}$, are arbitrary numbers.

But, if φ^{-1} is concave, then the reverse inequality is valid in (3.7) for $\delta_{\varphi^{-1}}\le 0$.

II) *If one of two equalities*

$$\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(A_i)=\sum_{i=1}^{n}\Phi_i(A_i)=\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(A_i)$$

is valid, then

$$\begin{aligned}\mathcal{M}_\varphi(\alpha,\mathbf{A},\mathbf{\Phi},1,n_1)&\le\varphi^{-1}\left(\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i\left(\varphi(A_i)\right)+\beta\delta_\varphi\widetilde{A}_{n_1}\right)\le\mathcal{M}_\varphi(1,\mathbf{A},\mathbf{\Phi},1,n)\\ &\le\varphi^{-1}\left(\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i\left(\varphi(A_i)\right)-\alpha\delta_\varphi\widetilde{A}_{n_1}\right)\le\mathcal{M}_\varphi(\beta,\mathbf{A},\mathbf{\Phi},n_1+1,n)\end{aligned} \tag{3.8}$$

holds for every continuous strictly monotone function $\varphi: I\to\mathbb{R}$ such that one of the following conditions

(i) *φ is convex and φ^{-1} is operator monotone,*
(i') *φ is concave and $-\varphi^{-1}$ is operator monotone,*

is satisfied, where $\delta_\varphi=\varphi(\bar{m})+\varphi(\bar{M})-2\varphi\left(\frac{\bar{m}+\bar{M}}{2}\right)$, $\widetilde{A}_{n_1}=\frac{1}{2}1_K-\frac{1}{\alpha(\bar{M}-\bar{m})}\times\sum_{i=1}^{n_1}\Phi_i\left(\left|A_i-\frac{\bar{m}+\bar{M}}{2}1_H\right|\right)$ and $\bar{m}\in[m,m_L]$, $\bar{M}\in[M_R,M]$, $\bar{m}<\bar{M}$, are arbitrary numbers.

But, if one of the following conditions

(ii) *φ is concave and φ^{-1} is operator monotone,*
(ii') *φ is convex and $-\varphi^{-1}$ is operator monotone,*

is satisfied, then the reverse inequality is valid in (3.8).

Proof. The inequalities (3.7) follows from Theorem 3.1 by replacing ψ with the identity function, while the inequalities (3.8) follows by replacing φ with the identity function and ψ with φ. □

Remark 3.3. *Let the assumptions of Theorem 3.1 be valid.*

1) We observe that if one of the following conditions

(i) $\psi\circ\varphi^{-1}$ is convex and ψ^{-1} is operator monotone,
(i') $\psi\circ\varphi^{-1}$ is concave and $-\psi^{-1}$ is operator monotone,

is satisfied, then the following obvious inequality (see Remark 2.4.1))

$$\begin{aligned}\mathcal{M}_{\varphi}(\beta,\mathbf{A},\mathbf{\Phi},n_1+1,n) &\le \psi^{-1}\left(\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i(\psi(A_i))-\delta_{\varphi}\widetilde{A}_{\beta}\right)\\ &\le \mathcal{M}_{\psi}(\beta,\mathbf{A},\mathbf{\Phi},n_1+1,n),\end{aligned}$$

holds, $\delta_{\varphi}=\varphi(\bar{m})+\varphi(\bar{M})-2\varphi\left(\frac{\bar{m}+\bar{M}}{2}\right)$, $\widetilde{A}_{\beta}=\frac{1}{2}1_K-\frac{1}{\bar{M}-\bar{m}}\left|\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_iA_i-\frac{\bar{m}+\bar{M}}{2}1_K\right|$ and $\bar{m}\in[m,m_L]$, $\bar{M}\in[M_R,M]$, $\bar{m}<\bar{M}$, are arbitrary numbers.

2) We denote by m_{φ} and M_{φ} the bounds of $\mathcal{M}_{\varphi}(1,\mathbf{A},\mathbf{\Phi},1,n)$. If $(m_{\varphi},M_{\varphi})\cap[m_i,M_i]=\emptyset$, $i=1,\dots,n_1$, and one of two following conditions

(i) $\psi\circ\varphi^{-1}$ is convex and ψ^{-1} is operator monotone
(ii) $\psi\circ\varphi^{-1}$ is concave and $-\psi^{-1}$ is operator monotone

is satisfied, then the double inequality (3.4) can be extended from the left side as follows

$$\begin{aligned}&\mathcal{M}_{\varphi}(1,\mathbf{A},\mathbf{\Phi},1,n)=\mathcal{M}_{\varphi}(1,\mathbf{A},\mathbf{\Phi},1,n_1)\le\psi^{-1}\left(\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i(f(A_i))-\delta_{\varphi,\psi}\widetilde{A}_{\alpha}\right)\\ &\le\mathcal{M}_{\psi}(\alpha,\mathbf{A},\mathbf{\Phi},1,n_1)\le\psi^{-1}\left(\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i\left(\psi(A_i)\right)+\beta\delta_{\varphi,\psi}\widetilde{A}_{\varphi,n_1,\alpha}\right)\\ &\le\mathcal{M}_{\psi}(1,\mathbf{A},\mathbf{\Phi},1,n)\le\psi^{-1}\left(\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i\left(\psi(A_i)\right)-\alpha\delta_{\varphi,\psi}\widetilde{A}_{\varphi,n_1,\alpha}\right)\\ &\le\mathcal{M}_{\psi}(\beta,\mathbf{A},\mathbf{\Phi},n_1+1,n),\end{aligned}$$

where $\delta_{\varphi,\psi}$ and $\widetilde{A}_{\varphi,n_1,\alpha}$ are defined by (3.2),

$$\widetilde{A}_{\alpha}=\frac{1}{2}1_K-\frac{1}{\bar{M}-\bar{m}}\left|\frac{1}{\alpha}\sum_{i=n_1+1}^{n}\Phi_iA_i-\frac{\bar{m}+\bar{M}}{2}1_K\right|.$$

As a special case of the quasi-arithmetic mean (3.1) we can study the weighted power mean as follows. For a subset $\{A_{p_1},\dots,A_{p_2}\}$ of $\{A_1,\dots,A_n\}$ we denote this mean by

$$M^{[r]}(\gamma,\mathbf{A},\mathbf{\Phi},p_1,p_2)=\begin{cases}\left(\dfrac{1}{\gamma}\displaystyle\sum_{i=p_1}^{p_2}\Phi_i\left(A_i^r\right)\right)^{1/r}, & r\in\mathbb{R}\backslash\{0\},\\ \exp\left(\dfrac{1}{\gamma}\displaystyle\sum_{i=p_1}^{p_2}\Phi_i\left(\ln\left(A_i\right)\right)\right), & r=0,\end{cases}$$

where $(A_{p_1},\dots,A_{p_2})$ are strictly positive operators, $(\Phi_{p_1},\dots,\Phi_{p_2})$ are positive linear mappings $\Phi_i:\mathcal{B}(H)\to\mathcal{B}(K)$ such that $\sum_{i=p_1}^{p_2}\Phi_i(1_H)=\gamma\,1_K$.

Under the same conditions, for convenience we introduce denotations as a special case of (3.2) as follows

$$\begin{aligned}\delta_{r,s}(m,M) &= \begin{cases} m^s+M^s-2\left(\frac{m^r+M^r}{2}\right)^{s/r}, & r\neq 0,\\ m^s+M^s-2\left(mM\right)^{s/2}, & r=0,\end{cases}\\ \widetilde{A}_r(m,M) &= \begin{cases}\frac{1}{2}1_K-\frac{1}{|M^r-m^r|}\left|\sum_{i=1}^n\Phi_i(A_i^r)-\frac{M^r+m^r}{2}1_K\right|, & r\neq 0,\\ \frac{1}{2}1_K-\left|\ln\left(\frac{M}{m}\right)\right|^{-1}\left|\sum_{i=1}^n\Phi_i(\ln A_i)-\ln\sqrt{Mm}1_K\right|, & r=0,\end{cases}\end{aligned}\tag{3.9}$$

where $m,M\in\mathbb{R}$, $0<m<M$ and $r,s\in\mathbb{R}$, $r\leq s$. Of course, we include implicitly that $\widetilde{A}_r(m,M)\equiv\widetilde{A}_{r,A}(m,M)$, where $A=\sum_{i=1}^n\Phi_i(A_i^r)$ for $r\neq 0$ and $A=\sum_{i=1}^n\Phi_i(\ln A_i)$ for $r=0$.

We obtain the following corollary by applying Theorem 3.1 to the above mean. This is an extension of [7, Corollary 13] and a refinement of [6, Corollary 3.4].

Corollary 3.4. *Let $(A_1,\dots,A_n)$ be an $n-$tuple of self-adjoint operators $A_i\in B(H)$ with the bounds m_i and M_i, $m_i\leq M_i$, $i=1,\dots,n$. Let $(\Phi_1,\dots,\Phi_n)$ be an $n-$tuple of positive linear mappings $\Phi_i:B(H)\to B(K)$, such that $\sum_{i=1}^{n_1}\Phi_i(1_H)=\alpha\,1_K$, $\sum_{i=n_1+1}^{n}\Phi_i(1_H)=\beta\,1_K$, where $1\leq n_1<n$, $\alpha,\beta>0$ and $\alpha+\beta=1$. Let*

$$(m_L,M_R)\cap[m_i,M_i]=\emptyset\quad\text{for}\quad i=n_1+1,\dots,n,\qquad m<M,$$

where $m_L=\min\{m_1,\dots,m_{n_1}\}$, $M_R=\max\{M_1,\dots,M_{n_1}\}$ and

$$\begin{aligned} m &= \begin{cases} m_L, & \text{if } \{M_i\colon M_i\leq m_L, i\in\{n_1+1,\dots,n\}\}=\emptyset,\\ \max\{M_i\colon M_i\leq m_L, i\in\{n_1+1,\dots,n\}\}, & \text{otherwise,}\end{cases}\\ M &= \begin{cases} M_R, & \text{if } \{m_i\colon m_i\geq M_R, i\in\{n_1+1,\dots,n\}\}=\emptyset,\\ \min\{m_i\colon m_i\geq M_R, i\in\{n_1+1,\dots,n\}\}, & \text{otherwise.}\end{cases}\end{aligned}$$

(i) *If either $r\leq s$, $s\geq 1$ or $r\leq s\leq -1$ and also one of two equalities*

$$\mathcal{M}^{[r]}(\alpha,\mathbf{A},\mathbf{\Phi},1,n_1)=\mathcal{M}^{[r]}(1,\mathbf{A},\mathbf{\Phi},1,n)=\mathcal{M}^{[r]}(\beta,\mathbf{A},\mathbf{\Phi},n_1+1,n)$$

is valid, then

$$\begin{aligned}\mathcal{M}^{[s]}(\alpha,\mathbf{A},\mathbf{\Phi},1,n_1) &\leq \left(\frac{1}{\alpha}\sum_{i=1}^{n_1}\Phi_i\left(A_i^s\right)+\beta\delta_{r,s}\widetilde{A}_{s,n_1,\alpha}\right)^{1/s}\leq\mathcal{M}^{[s]}(1,\mathbf{A},\mathbf{\Phi},1,n)\\ &\leq\left(\frac{1}{\beta}\sum_{i=n_1+1}^{n}\Phi_i\left(A_i^s\right)-\alpha\delta_{r,s}\widetilde{A}_{s,n_1,\alpha}\right)^{1/s}\leq\mathcal{M}^{[s]}(\beta,\mathbf{A},\mathbf{\Phi},n_1+1,n)\end{aligned}$$

holds, where $\delta_{r,s} \geq 0$ *and* $\widetilde{A}_{s,n_1,\alpha} \geq 0$.

In this case, we assume that $\delta_{r,s} \equiv \delta_{r,s}(\bar{m}, \bar{M})$, $\widetilde{A}_{s,n_1,\alpha} \equiv \widetilde{A}_{s,n_1,\alpha}(\bar{m}, \bar{M})$ *are defined by* (3.9) *and* $\bar{m} \in [m, m_L]$, $\bar{M} \in [M_R, M]$, $\bar{m} < \bar{M}$, *are arbitrary numbers.*

(ii) *If either* $r \leq s$, $r \leq -1$ *or* $1 \leq r \leq s$ *and also one of two equalities*

$$\mathcal{M}^{[s]}(\alpha, \mathbf{A}, \mathbf{\Phi}, 1, n_1) = \mathcal{M}^{[s]}(1, \mathbf{A}, \mathbf{\Phi}, 1, n) = \mathcal{M}^{[s]}(\beta, \mathbf{A}, \mathbf{\Phi}, n_1+1, n)$$

is valid, then

$$\mathcal{M}^{[r]}(\alpha, \mathbf{A}, \mathbf{\Phi}, 1, n_1) \geq \left(\frac{1}{\alpha} \sum_{i=1}^{n_1} \Phi_i\left(A_i^r\right) + \beta \delta_{s,r} \widetilde{A}_{r,n_1,\alpha} \right)^{1/r} \geq \mathcal{M}^{[r]}(1, \mathbf{A}, \mathbf{\Phi}, 1, n)$$
$$\geq \left(\frac{1}{\beta} \sum_{i=n_1+1}^{n} \Phi_i\left(A_i^r\right) - \alpha \delta_{s,r} \widetilde{A}_{r,n_1,\alpha} \right)^{1/r} \geq \mathcal{M}^{[r]}(\beta, \mathbf{A}, \mathbf{\Phi}, n_1+1, n)$$

holds, where $\delta_{s,r} \leq 0$ *and* $\widetilde{A}_{s,n_1,\alpha} \geq 0$.

In this case, we assume that $\delta_{s,r} \equiv \delta_{s,r}(\bar{m}, \bar{M})$, $\widetilde{A}_{r,n_1,\alpha} \equiv \widetilde{A}_{r,n_1,\alpha}(\bar{m}, \bar{M})$ *are defined by* (3.9) *and* $\bar{m} \in [m, m_L]$, $\bar{M} \in [M_R, M]$, $\bar{m} < \bar{M}$, *are arbitrary numbers.*

Proof. In the case (i) we put $\psi(t) = t^s$ and $\varphi(t) = t^r$ if $r \neq 0$ or $\varphi(t) = \ln t$ if $r \neq 0$ in Theorem 3.1. In the case (ii) we put $\psi(t) = t^r$ and $\varphi(t) = t^s$ if $s \neq 0$ or $\varphi(t) = \ln t$ if $s \neq 0$. We omit the details. □

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