Some Operator Functions Implying Order Preserving Inequalities (Structure of operators and related current topics)

Author(s)
Giga, Mariko

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Some Operator Functions 
Implying Order Preserving Inequalities

日本医科大学 数学教室 儀我 真理子 (Mariko Giga) 
(Department of Mathematics, Nippon Medical School)

This paper is a resume based on my talk at “Structure of operators and related recent topics” which has been held at RIMS on January 24, 2003 and also this is early announcement of [9].

As an application of our previous result [Theorem 1, 11], we show a simple proof of the following result:

If $A \geq B \geq C \geq 0$ with $A > 0$ and $B > 0$, then for each $t \in [0,1]$, and $p \geq t$, the following (i) and (ii) hold for a fixed real number $q$ and they are mutually equivalent:

(i) if $q \geq 0$, then

$$G_{p,q,t}(A, B, C, r, s) = A^{\frac{r}{2}} \left\{ A^\frac{r}{2} (B^\frac{-t}{2} C^p B^\frac{-t}{2})^s A^\frac{r}{2} \right\}^{\frac{q-t+r}{(p-t)s+r}} A^{\frac{-r}{2}}$$

is decreasing function for $r \geq t$ and $s \geq 1$ such that $(p-t)s \geq q-t$.

(ii) if $p \geq q$, then

$$G_{p,q,t}(A, B, C, r, s) = A^{\frac{r}{2}} \left\{ A^\frac{r}{2} (B^\frac{-t}{2} C^p B^\frac{-t}{2})^s A^\frac{r}{2} \right\}^{\frac{q-t+r}{(p-t)s+r}} A^{\frac{-r}{2}}$$

is decreasing function for $s \geq 1$ and $r \geq \max\{t, t-q\}$.

This result is further extension of our previous paper [Theorem 2, 11]. On the other hand, M.Uchiyama [17] shows the following interesting result

(iii) If $A \geq B \geq C \geq 0$ with $B > 0$, then for each $t \in [0,1]$ and $p \geq 1$,

$$A^{1-t+r} \geq \left\{ A^{\frac{r}{2}} (B^\frac{-t}{2} C^p B^\frac{-t}{2})^s A^\frac{r}{2} \right\}^{\frac{q-t+r}{(p-t)s+r}}$$

holds for $r \geq t$ and $s \geq 1$.

We show that (i) is equivalent to (iii), that is, follows from each other and also as an application of our previous result [Theorem 1, 11], we give a simple proof of M.Uchiyama’s result [Theorem 3.4, 17].
1 Introduction.

A capital letter means a bounded linear operator on a Hilbert space.

**Theorem L-H** (Löwner-Heinz inequality) [13][15].

\[ A \geq B \geq 0 \text{ ensures } A^\alpha \geq B^\alpha \text{ for all } \alpha \in [0, 1]. \]

Theorem L-H is very useful, but the condition " \( \alpha \in [0, 1] \) " is too restrictive to calculate operator inequalities, the following result has been obtained from this point of view.

**Theorem F** (Furuta inequality) [4].

If \( A \geq B \geq 0 \), then for each \( r \geq 0 \),

(i) \( (B^\frac{r}{2} A^p B^\frac{r}{2})^\frac{1}{r} \geq (B^\frac{r}{2} B^p B^\frac{r}{2})^\frac{1}{r} \)

and

(ii) \( (A^\frac{r}{2} A^p A^\frac{r}{2})^\frac{1}{r} \geq (A^\frac{r}{2} B^p A^\frac{r}{2})^\frac{1}{r} \)

hold for \( p \geq 0 \) and \( q \geq 1 \) with \( (1 + r)q \geq p + r \).

Alternative proofs are in [14][1] and one page proof in [5]. It is proved in [16] that The domain drawn for \( p, q \) and \( r \) in Figure is the best possible one for Theorem F. The following Theorem G is an extension of Theorem F.

**Theorem G** [6][2]. If \( A \geq B \geq 0 \) with \( A > 0 \), then for \( t \in [0, 1] \) and \( p \geq 1 \)

\[ A^{1-t+r} \geq \{A^\frac{r}{2} (A^\frac{-t}{2} B^p A^\frac{-t}{2})^{\frac{s}{u}} A^\frac{r}{2}\}^{\frac{1}{(1-t)u+r}} \]

holds for \( s \geq 1 \) and \( r \geq t \).

Very recently M.Uchiyama shows the following interesting extension of Theorem G.

**Theorem U** [17]. If \( A \geq B \geq C \geq 0 \) with \( B > 0 \), then for \( t \in [0, 1] \) and \( p \geq 1 \)

\[ A^{1-t+r} \geq \{A^\frac{r}{2} (B^\frac{-t}{2} C^p B^\frac{-t}{2})^{s} A^\frac{r}{2}\}^{\frac{1}{(1-t)s+r}} \]

holds for \( s \geq 1 \) and \( r \geq t \).

We show that Theorem U is equivalent to (i) of Theorem 1 under below, that is, follows from each other and also as an application of our previous result [Theorem 1, 11], we give a simple proof of M.Uchiyama’s result [Theorem 3.4, 17].
Operator Functions Implying Theorem U.

**Theorem 1.** If $A \geq B \geq C \geq 0$ with $A > 0$ and $B > 0$, then for each $t \in [0, 1]$, and $p \geq t$, the following (i) and (ii) hold for a fixed real number $q$ and they are mutually equivalent:

(i) if $q \geq 0$, then

$$G_{p,q,t}(A, B, C, r, s) = A^{\frac{-r}{2}} \{A^{\frac{r}{2}} (B^{\frac{t}{2}} C^{p} B^{\frac{t}{2}})^{s} A^{\frac{r}{2}}\}^{\frac{q-t+r}{(p-t)\iota+r}} A^{\frac{-r}{2}}$$

is decreasing function for $r \geq t$ and $s \geq 1$ such that $(p-t)s \geq q-t$.

(ii) if $p \geq q$, then

$$G_{p,q,t}(A, B, C, r, s) = A^{\frac{-r}{2}} \{A^{\frac{r}{2}} (B^{\frac{t}{2}} C^{p} B^{\frac{t}{2}})^{s} A^{\frac{r}{2}}\}^{\frac{q-t+r}{(p-t)\cdot+r}} A^{\frac{-r}{2}}$$

is decreasing function for $s \geq 1$ and $r \geq \max\{t, t-q\}$.

We need the following results to prove Theorem 1.

**Theorem A [11].** Let $A$ and $B$ be positive invertible operators on a Hilbert space satisfying

$$A \geq (A^{\frac{1}{2}} B A^{\frac{1}{2}})^{\frac{\alpha_{0}}{\alpha_{0}+\beta_{0}}}$$

for fixed $\alpha_{0} \geq 0$ and $\beta_{0} \geq 0$ with $\alpha_{0} + \beta_{0} > 0$.

Then the following (i) and (ii) hold and they are mutually equivalent:

(i) for any fixed $\delta \geq -\beta_{0}$,

$$f(\lambda, \mu) = A^{\frac{-\mu}{2}} (A^{\frac{\delta}{2}} B^{\mu} A^{\frac{\epsilon}{2}})_{\alpha_{0}+\beta_{0}} A^{\frac{-\mu}{2}}$$

is decreasing function for $\mu \geq 1$ and $\lambda \geq 1$ such that $\alpha_{0} \lambda \geq \delta$.

(ii) for any fixed $\delta \leq \alpha_{0}$,

$$f(\lambda, \mu) = A^{\frac{-\mu}{2}} (A^{\frac{\delta}{2}} B^{\lambda} A^{\frac{\epsilon}{2}})_{\alpha_{0}+\beta_{0}} A^{\frac{-\mu}{2}}$$

is decreasing function for $\lambda \geq 1$ and $\mu \geq 1$ such that $\beta_{0} \mu \geq -\delta$.

**Lemma B [6].** Let $X$ be a positive invertible operator and $Y$ be an invertible operator. For any real number $\lambda$,

$$(YXY^*)^{\lambda} = YX^{\frac{1}{2}} (X^{\frac{1}{2}} Y^* Y X^{\frac{1}{2}})^{\lambda-1} X^{\frac{1}{2}} Y^*.$$
3 Equivalence Relation Associated with Theorem 1.

We show the following equivalence relation between Theorem 1 and related operator inequalities.

**Theorem 2.** The following (i),(ii),(iii) and (iv) hold and follow from each other.

(i) If $A \geq B \geq C \geq 0$ with $A > 0$ and $B > 0$, then for each $t \in [0, 1]$ and $p \geq 1$,

$$A^{1-t+r} \geq \{A^{\frac{r}{2}} (B^{\frac{-t}{2}}C^pB^{\frac{-t}{2}})^{s}A^{\frac{r}{2}}\}^{\frac{1-t+r}{(p-t)r}}$$

holds for $r \geq t$ and $s \geq 1$.

(ii) If $A \geq B \geq C \geq 0$ with $A > 0$ and $B > 0$, then for each $1 \geq q \geq t \geq 0$ and $p \geq q$,

$$A^{q-t+r} \geq \{A^{\frac{r}{2}} (B^{\frac{-q}{2}}C^pB^{\frac{-q}{2}})^{s}A^{\frac{r}{2}}\}^{\frac{q-t+r}{(p-q)s}}$$

holds for $r \geq t$ and $s \geq 1$.

(iii) If $A \geq B \geq C \geq 0$ with $A > 0$ and $B > 0$, then for each $t \in [0, 1]$ and $p \geq 1$,

$$F_{p,t}(A, B, C, r, s) = A^{\frac{r}{2}} \{A^{\frac{r}{2}} (B^{\frac{-r}{2}}C^pB^{\frac{-r}{2}})^{s}A^{\frac{r}{2}}\}^{\frac{1-t}{(p-t)r}}A^{\frac{r}{2}}$$

is decreasing function for $r \geq t$ and $s \geq 1$.

(iv) If $A \geq B \geq C \geq 0$ with $A > 0$ and $B > 0$, then for each $t \in [0, 1]$, $q \geq 0$ and $p \geq t$,

$$G_{p,q,t}(A, B, r, s) = A^{\frac{r}{2}} \{A^{\frac{r}{2}} (B^{\frac{-r}{2}}C^pB^{\frac{-r}{2}})^{s}A^{\frac{r}{2}}\}^{\frac{t}{(p-t)s}}A^{\frac{r}{2}}$$

is decreasing function for $r \geq t$ and $s \geq 1$ such that $(p-t)s \geq q-t$.

We remark that Theorem 2 is an extension of [10], a proof of (i) of Theorem 2 is in [Proposition 4.1, 17], one page proof of (i) by using Theorem G itself is in [8], and also mean theoretic proof of (i) is in [3].

4 Satellite Inequalities.

As simple applications of Theorem 1 and Theorem 2, we show the following satellite inequalities.
Theorem 3. If $A \geq B \geq C > 0$, then the following inequalities (i) and (ii) hold for each $t \in [0,1]$, $p \geq 1$, $r \geq t$ and $s \geq 1$:

(i) $$B^\frac{t}{2}C^\frac{r}{2}\{C^\frac{r}{2}(B^\frac{-t}{2}A^pB^\frac{-t}{2})^sC^\frac{r}{2}\}^\frac{1+r-t}{(p-t)\epsilon+r}C^\frac{-r}{2}B^\frac{t}{2} \geq A \geq B \geq C \geq B^\frac{t}{2}A^\frac{-t}{2}\{A^\frac{t}{2}(B^\frac{-t}{2}C^pB^\frac{-t}{2})^sA^\frac{t}{2}\}^\frac{1}{(p-t)s+r}A^\frac{-t}{2}B^\frac{t}{2}$$

(ii) $$B^\frac{t}{2}C^\frac{r}{2}\{C^\frac{r}{2}(B^\frac{-t}{2}A^pB^\frac{-t}{2})^sC^\frac{r}{2}\}^\frac{1+r-t}{(p-t)\epsilon+r}C^\frac{-r}{2}B^\frac{t}{2} \geq A \geq B \geq C \geq B^\frac{t}{2}A^\frac{-r}{2}\{A^\frac{r}{2}(B^\frac{-t}{2}C^pB^\frac{-t}{2})^sA^\frac{r}{2}\}^\frac{1+r-t}{(p-t)\epsilon+r}A^\frac{-r}{2}B^\frac{t}{2}.$$

Corollary 4. If $A \geq B > 0$, then the following inequalities (i) and (ii) hold for each $t \in [0,1]$, $p \geq 1$, $r \geq t$ and $s \geq 1$:

(i) $$B^{-\frac{(r-t)}{2}}\{B^\frac{r}{2}(B^\frac{-t}{2}A^pB^\frac{-t}{2})^sB^\frac{r}{2}\}^\frac{1+r-t}{(p-t)\epsilon+r}B^{-\frac{(r-t)}{2}} \geq \{B^\frac{t}{2}(B^\frac{-t}{2}A^pB^\frac{-t}{2})^sB^\frac{t}{2}\}^\frac{1}{(p-t)s+r} \geq A \geq B \geq \{A^\frac{t}{2}(A^\frac{-t}{2}B^pA^\frac{-t}{2})^sA^\frac{t}{2}\}^\frac{1}{(p-t)s+r}A^{-\frac{(r-t)}{2}}$$

(ii) $$B^{-\frac{(r-t)}{2}}\{B^\frac{r}{2}(B^\frac{-t}{2}A^pB^\frac{-t}{2})^sB^\frac{r}{2}\}^\frac{1+r-t}{(p-t)\epsilon+r}B^{-\frac{(r-t)}{2}} \geq B^{-\frac{(r-t)}{2}}\{B^\frac{r}{2}(B^\frac{-t}{2}A^pB^\frac{-t}{2})^sB^\frac{r}{2}\}^\frac{1+r-t}{(p-t)\epsilon+r}B^{-\frac{(r-t)}{2}} \geq A \geq B \geq A^{-\frac{(r-t)}{2}}\{A^\frac{t}{2}(A^\frac{-t}{2}B^pA^\frac{-t}{2})^sA^\frac{t}{2}\}^\frac{1}{(p-t)s+r}A^{-\frac{(r-t)}{2}}.$$
Corollary 5. If $A \geq B > 0$, then the following inequality holds for $p \geq 1$ and $r \geq 0$

$$B^{\frac{r}{2}}(B^{\frac{r}{2}}A^{p}B^{\frac{r}{2}})^{\frac{1+r}{p+r}}B^{\frac{r}{2}} \geq A \geq B \geq A^{\frac{-r}{2}}(B^{\frac{r}{2}}A^{p}B^{\frac{r}{2}})^{\frac{1+r}{p+r}}A^{\frac{-r}{2}}.$$ 

5 M.Uchiyama’s Result via Theorem A.

The following result is contained in Theorem 3.4 of [17].

**Theorem V.** Let $A$ and $B$ be both positive invertible operators. Also let $a, b, \text{ and } c$ be positive real numbers and $d$ a real number. Define $F(r, s)$ and $G(r, s)$ by

$$F(r, s) = A^{\frac{r}{2}}(A^{\frac{r}{2}}B^{a}A^{\frac{r}{2}})^{\frac{r+d}{r+s}}A^{\frac{r}{2}} \quad \text{for } r > 0, \, s > 0$$

and

$$G(r, s) = A^{\frac{r}{2}}(A^{\frac{r}{2}}B^{a}A^{\frac{r}{2}})^{\frac{r+d}{r+s}}A^{\frac{r}{2}} \quad \text{for } r > 0, \, s > 0 \text{ with } 0 \leq \frac{r+d}{r+s} \leq 1.$$ 

Let $a > 0, b > 0$ and $-a \leq d \leq bc$. Then for $r_2 \geq r_1 \geq a$ and $s_2 \geq s_1 \geq b$ the following hold:

(a) if $F(a, b) \leq 1$, then $G(r_2, s_2) \leq G(r_1, s_1)$

(b) if $F(a, b) \geq 1$, then $G(r_2, s_2) \geq G(r_1, s_1)$.

On the other hand, in Theorem A replacing $A$ by $A^{\beta_0}$ and $B$ by $B^{\alpha_0}$, then we have the following result in [12].

**Corollary C.** Let $A$ and $B$ be positive invertible operators on a Hilbert space satisfying

$$A^{\beta_0} \geq (A^{\frac{\beta_0}{2}}B^{\alpha_0}A^{\frac{\beta_0}{2}})^{\frac{\beta_0}{\alpha_0 + \beta_0}} \quad \text{for fixed } \alpha_0 > 0 \text{ and } \beta_0 > 0.$$ 

Then for any fixed $\delta \geq -\beta_0$,

$$f(\alpha, \beta) = A^{\frac{\alpha}{2}}(A^{\frac{\beta}{2}}B^{\alpha}A^{\frac{\beta}{2}})^{\frac{\alpha + \beta}{\alpha + \beta}}A^{\frac{-\beta}{2}}$$

is decreasing function of $\alpha$ and $\beta$ such that $\alpha \geq \max\{\delta, \alpha_0\}$ and $\beta \geq \beta_0$.

We can give a proof of Theorem V via Corollary C.

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