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INEQUALITIES FOR QUANTUM f-DIVERGENCE OF CONVEX FUNCTIONS AND MATRICES

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Abstract. Some inequalities for quantum f-divergence of matrices are obtained. It is shown that for normalised convex functions it is nonnegative. Some upper bounds for quantum f-divergence in terms of variational and χ^2-distance are provided. Applications for some classes of divergence measures such as Umegaki and Tsallis relative entropies are also given.

1. Introduction

Let $(X, \mathcal{A})$ be a measurable space satisfying $|\mathcal{A}| > 2$ and μ be a σ-finite measure on $(X, \mathcal{A})$. Let $\mathcal{P}$ be the set of all probability measures on $(X, \mathcal{A})$ which are absolutely continuous with respect to μ. For P, $Q \in \mathcal{P}$, let $p = \frac{dP}{d\mu}$ and $q = \frac{dQ}{d\mu}$ denote the *Radon-Nikodym* derivatives of P and Q with respect to μ.

Two probability measures P, $Q \in \mathcal{P}$ are said to be *orthogonal* and we denote this by $Q \perp P$ if

$$P(\{q = 0\}) = Q(\{p = 0\}) = 1.$$

Let $f : [0, \infty) \to (-\infty, \infty]$ be a convex function that is continuous at 0, i.e., $f(0) = \lim_{u \downarrow 0} f(u)$.

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In 1963, I. Csiszár [3] introduced the concept of f-divergence as follows.

Definition 1. Let P, $Q \in \mathcal{P}$. Then

$$I_f(Q,P) = \int_X p(x) f\left[\frac{q(x)}{p(x)}\right] d\mu(x), \tag{1.1}$$

is called the f-divergence of the probability distributions Q and P.

Remark 1. Observe that, the integrand in the formula (1.1) is undefined when $p(x) = 0$. The way to overcome this problem is to postulate for f as above that

$$0 f\left[\frac{q(x)}{0}\right] = q(x) \lim_{u \downarrow 0}\left[u f\left(\frac{1}{u}\right)\right], \; x \in X. \tag{1.2}$$

We now give some examples of f-divergences that are well-known and often used in the literature (see also [2]).

1.1. The Class of χ^α-Divergences. The f-divergences of this class, which is generated by the function χ^α, $\alpha \in [1,\infty)$, defined by

$$\chi^\alpha(u) = |u-1|^\alpha, \quad u \in [0,\infty)$$

have the form

$$I_f(Q,P) = \int_X p\left|\frac{q}{p} - 1\right|^\alpha d\mu = \int_X p^{1-\alpha}|q-p|^\alpha d\mu. \tag{1.3}$$

From this class only the parameter $\alpha = 1$ provides a distance in the topological sense, namely the *total variation distance* $V(Q,P) = \int_X |q-p|\, d\mu$. The most prominent special case of this class is, however, *Karl Pearson's* χ^2*-divergence*

$$\chi^2(Q,P) = \int_X \frac{q^2}{p} d\mu - 1$$

that is obtained for $\alpha = 2$.

1.2. Dichotomy Class. From this class, generated by the function $f_\alpha : [0,\infty) \to \mathbb{R}$

$$f_\alpha(u) = \begin{cases} u - 1 - \ln u & \text{for } \alpha = 0; \\ \frac{1}{\alpha(1-\alpha)}[\alpha u + 1 - \alpha - u^\alpha] & \text{for } \alpha \in \mathbb{R}\setminus\{0,1\}; \\ 1 - u + u\ln u & \text{for } \alpha = 1; \end{cases}$$

only the parameter $\alpha = \frac{1}{2}$ $\left(f_{\frac{1}{2}}(u) = 2\left(\sqrt{u} - 1\right)^2\right)$ provides a distance, namely, the *Hellinger distance*

$$H(Q,P) = \left[\int_X \left(\sqrt{q} - \sqrt{p}\right)^2 d\mu\right]^{\frac{1}{2}}.$$

Another important divergence is the *Kullback-Leibler divergence* obtained for $\alpha = 1$,

$$KL(Q,P) = \int_X q \ln\left(\frac{q}{p}\right) d\mu.$$

1.3. Matsushita's Divergences. The elements of this class, which is generated by the function φ_α, $\alpha \in (0,1]$ given by

$$\varphi_\alpha(u) := |1 - u^\alpha|^{\frac{1}{\alpha}}, \quad u \in [0,\infty),$$

are prototypes of metric divergences, providing the distances $\left[I_{\varphi_\alpha}(Q,P)\right]^\alpha$.

1.4. Puri-Vincze Divergences. This class is generated by the functions Φ_α, $\alpha \in [1,\infty)$ given by

$$\Phi_\alpha(u) := \frac{|1-u|^\alpha}{(u+1)^{\alpha-1}}, \quad u \in [0,\infty).$$

It has been shown in [19] that this class provides the distances $\left[I_{\Phi_\alpha}(Q,P)\right]^{\frac{1}{\alpha}}$.

1.5. Divergences of Arimoto-type. This class is generated by the functions

$$\Psi_\alpha(u) := \begin{cases} \frac{\alpha}{\alpha-1}\left[(1+u^\alpha)^{\frac{1}{\alpha}} - 2^{\frac{1}{\alpha}-1}(1+u)\right] & \text{for } \alpha \in (0,\infty)\setminus\{1\}; \\ (1+u)\ln 2 + u\ln u - (1+u)\ln(1+u) & \text{for } \alpha = 1; \\ \frac{1}{2}|1-u| & \text{for } \alpha = \infty. \end{cases}$$

It has been shown in [21] that this class provides the distances $\left[I_{\Psi_\alpha}(Q,P)\right]^{\min\left(\alpha,\frac{1}{\alpha}\right)}$ for $\alpha \in (0,\infty)$ and $\frac{1}{2}V(Q,P)$ for $\alpha = \infty$.

For f continuous convex on $[0,\infty)$ we obtain the $*$-*conjugate* function of f by

$$f^*(u) = uf\left(\frac{1}{u}\right), \quad u \in (0,\infty)$$

and

$$f^{*}(0)=\lim_{u\downarrow 0} f^{*}(u).$$

It is also known that if f is continuous convex on $[0,\infty)$ then so is f^{*}.

The following two theorems contain the most basic properties of f-divergences. For their proofs we refer the reader to Chapter 1 of [20] (see also [2]).

Theorem 1 (Uniqueness and Symmetry Theorem). *Let f, f_1 be continuous convex on $[0,\infty)$. We have*

$$I_{f_1}(Q,P)=I_f(Q,P),$$

for all $P,Q\in\mathcal{P}$ if and only if there exists a constant $c\in\mathbb{R}$ such that

$$f_1(u)=f(u)+c(u-1),$$

for any $u\in[0,\infty)$.

Theorem 2 (Range of Values Theorem). *Let $f:[0,\infty)\to\mathbb{R}$ be a continuous convex function on $[0,\infty)$.*

For any $P,Q\in\mathcal{P}$, we have the double inequality

$$f(1)\le I_f(Q,P)\le f(0)+f^{*}(0). \tag{1.4}$$

(i) If $P=Q$, then the equality holds in the first part of (1.4).

If f is strictly convex at 1, then the equality holds in the first part of (1.4) if and only if $P=Q$;

(ii) If $Q\perp P$, then the equality holds in the second part of (1.4).

If $f(0)+f^{*}(0)<\infty$, then equality holds in the second part of (1.4) if and only if $Q\perp P$.

The following result is a refinement of the second inequality in Theorem 2 (see [2, Theorem 3]).

Theorem 3. *Let f be a continuous convex function on $[0,\infty)$ with $f(1)=0$ (f is normalised) and $f(0)+f^{*}(0)<\infty$. Then*

$$0\le I_f(Q,P)\le\frac{1}{2}\left[f(0)+f^{*}(0)\right]V(Q,P) \tag{1.5}$$

for any $Q,P\in\mathcal{P}$.

For other inequalities for f-divergence see [1], [5]- [15].

Motivated by the above results, in this paper we obtain some new inequalities for quantum f-divergence of matrices. It is shown that for normalised convex functions it is nonnegative. Some upper bounds for quantum f-divergence in terms of variational and χ^2-distance are provided. Applications for some classes of divergence measures such as Umegaki and Tsallis relative entropies are also given.

2. Quantum f-Divergence

Quasi-entropy was introduced by Petz in 1985, [22] as the quantum generalization of Csiszár's f-divergence in the setting of matrices or von Neumann algebras. The important special case was the relative entropy of Umegaki and Araki.

In what follows some inequalities for the quantum f-divergence of convex functions in the finite dimensional setting are provided.

Let $\mathcal{M}$ denotes the algebra of all $n \times n$ matrices with complex entries and $\mathcal{M}^+$ the subclass of all positive matrices.

On complex Hilbert space $(\mathcal{M}, \langle \cdot, \cdot \rangle_2)$, where the *Hilbert-Schmidt inner product* is defined by

$$\langle U, V \rangle_2 := \operatorname{tr}(V^* U), \; U, \; V \in \mathcal{M},$$

for A, $B \in \mathcal{M}^+$ consider the operators $\mathfrak{L}_A : \mathcal{M} \to \mathcal{M}$ and $\mathfrak{R}_B : \mathcal{M} \to \mathcal{M}$ defined by

$$\mathfrak{L}_A T := AT \text{ and } \mathfrak{R}_B T := TB.$$

We observe that they are well defined and since

$$\langle \mathfrak{L}_A T, T \rangle_2 = \langle AT, T \rangle_2 = \operatorname{tr}(T^* AT) = \operatorname{tr}\left(|T^*|^2 A\right) \geq 0$$

and

$$\langle \mathfrak{R}_B T, T \rangle_2 = \langle TB, T \rangle_2 = \operatorname{tr}(T^* TB) = \operatorname{tr}\left(|T|^2 B\right) \geq 0$$

for any $T \in \mathcal{M}$, they are also positive in the operator order of $\mathcal{B}(\mathcal{M})$, the Banach algebra of all bounded operators on $\mathcal{M}$ with the norm $\|\cdot\|_2$ where $\|T\|_2 = \operatorname{tr}\left(|T|^2\right)$, $T \in \mathcal{M}$.

Since $\operatorname{tr}\left(|X^*|^2\right) = \operatorname{tr}\left(|X|^2\right)$ for any $X \in \mathcal{M}$, then also

$$\begin{aligned}\operatorname{tr}(T^*AT) &= \operatorname{tr}\left(T^*A^{1/2}A^{1/2}T\right) = \operatorname{tr}\left(\left(A^{1/2}T\right)^* A^{1/2}T\right) \\ &= \operatorname{tr}\left(\left|A^{1/2}T\right|^2\right) = \operatorname{tr}\left(\left|\left(A^{1/2}T\right)^*\right|^2\right) = \operatorname{tr}\left(\left|T^*A^{1/2}\right|^2\right)\end{aligned}$$

for $A \geq 0$ and $T \in \mathcal{M}$.

We observe that $\mathfrak{L}_A$ and $\mathfrak{R}_B$ are commutative, therefore the product $\mathfrak{L}_A\mathfrak{R}_B$ is a selfadjoint positive operator in $\mathcal{B}(\mathcal{M})$ for any positive matrices A, $B \in \mathcal{M}^+$.

For A, $B \in \mathcal{M}^+$ with B invertible, we define the *Araki transform* $\mathfrak{A}_{A,B} : \mathcal{M} \to \mathcal{M}$ by $\mathfrak{A}_{A,B} := \mathfrak{L}_A\mathfrak{R}_{B^{-1}}$. We observe that for $T \in \mathcal{M}$ we have $\mathfrak{A}_{A,B}T = ATB^{-1}$ and

$$\langle \mathfrak{A}_{A,B}T, T\rangle_2 = \left\langle ATB^{-1}, T\right\rangle_2 = \operatorname{tr}\left(T^*ATB^{-1}\right).$$

Observe also, by the properties of trace, that

$$\begin{aligned}\operatorname{tr}\left(T^*ATB^{-1}\right) &= \operatorname{tr}\left(B^{-1/2}T^*A^{1/2}A^{1/2}TB^{-1/2}\right) \\ &= \operatorname{tr}\left(\left(A^{1/2}TB^{-1/2}\right)^*\left(A^{1/2}TB^{-1/2}\right)\right) = \operatorname{tr}\left(\left|A^{1/2}TB^{-1/2}\right|^2\right)\end{aligned}$$

giving that

$$\langle \mathfrak{A}_{A,B}T, T\rangle_2 = \operatorname{tr}\left(\left|A^{1/2}TB^{-1/2}\right|^2\right) \geq 0 \tag{2.1}$$

for any $T \in \mathcal{M}$.

We observe that, by the definition of operator order and by (2.1) we have $r1_{\mathcal{M}} \leq \mathfrak{A}_{A,B} \leq R1_{\mathcal{M}}$ for some $R \geq r \geq 0$ if and only if

$$r \operatorname{tr}\left(|T|^2\right) \leq \operatorname{tr}\left(\left|A^{1/2}TB^{-1/2}\right|^2\right) \leq R \operatorname{tr}\left(|T|^2\right) \tag{2.2}$$

for any $T \in \mathcal{M}$.

We also notice that a sufficient condition for (2.2) to hold is that the following inequality in the operator order of $\mathcal{M}$ is satisfied

$$r|T|^2 \leq \left|A^{1/2}TB^{-1/2}\right|^2 \leq R|T|^2 \tag{2.3}$$

for any $T \in \mathcal{B}_2(H)$.

Let U be a selfadjoint linear operator on a complex Hilbert space $(K; \langle\cdot,\cdot\rangle)$. The *Gelfand map* establishes a $*$-isometrically isomorphism Φ between the set $C(\operatorname{Sp}(U))$ of all *continuous functions* defined on the *spectrum* of U, denoted $\operatorname{Sp}(U)$, and the C^*-algebra $C^*(U)$ generated by U and the identity operator 1_K on K as follows:

For any $f, g \in C(\mathrm{Sp}(U))$ and any $\alpha, \beta \in \mathbb{C}$ we have

(i) $\Phi(\alpha f + \beta g) = \alpha\Phi(f) + \beta\Phi(g)$;

(ii) $\Phi(fg) = \Phi(f)\Phi(g)$ and $\Phi(\bar{f}) = \Phi(f)^*$;

(iii) $\|\Phi(f)\| = \|f\| := \sup_{t\in\mathrm{Sp}(U)} |f(t)|$;

(iv) $\Phi(f_0) = 1_K$ and $\Phi(f_1) = U$, where $f_0(t) = 1$ and $f_1(t) = t$, for $t \in \mathrm{Sp}(U)$.

With this notation we define

$$f(U) := \Phi(f) \quad \text{for all } f \in C(\mathrm{Sp}(U))$$

and we call it the *continuous functional calculus* for a selfadjoint operator U.

If U is a selfadjoint operator and f is a real valued continuous function on $\mathrm{Sp}(U)$, then $f(t) \geq 0$ for any $t \in \mathrm{Sp}(U)$ implies that $f(U) \geq 0$, i.e. $f(U)$ is a positive operator on K. Moreover, if both f and g are real valued functions on $\mathrm{Sp}(U)$ then the following important property holds:

$$\text{(P)} \quad f(t) \geq g(t) \quad \text{for any} \quad t \in \mathrm{Sp}(U) \quad \text{implies that} \quad f(U) \geq g(U)$$

in the operator order of $B(K)$.

Let $f : [0, \infty) \to \mathbb{R}$ be a continuous function. Utilising the continuous functional calculus for the Araki selfadjoint operator $\mathfrak{A}_{Q,P} \in \mathcal{B}(\mathcal{M})$ we can define the *quantum f-divergence* for Q, $P \in S_1(\mathcal{M}) := \{P \in \mathcal{M},\ P \geq 0 \text{ with } \operatorname{tr}(P) = 1\}$ and P invertible, by

$$S_f(Q, P) := \left\langle f(\mathfrak{A}_{Q,P}) P^{1/2}, P^{1/2} \right\rangle_2 = \operatorname{tr}\left(P^{1/2} f(\mathfrak{A}_{Q,P}) P^{1/2}\right).$$

If we consider the continuous convex function $f : [0, \infty) \to \mathbb{R}$, with $f(0) := 0$ and $f(t) = t \ln t$ for $t > 0$ then for Q, $P \in S_1(\mathcal{M})$ and Q, P invertible we have

$$S_f(Q, P) = \operatorname{tr}[Q(\ln Q - \ln P)] =: U(Q, P),$$

which is the *Umegaki relative entropy.*

If we take the continuous convex function $f : [0, \infty) \to \mathbb{R}$, $f(t) = |t - 1|$ for $t \geq 0$ then for Q, $P \in S_1(H)$ with P invertible we have

$$S_f(Q, P) = \operatorname{tr}(|Q - P|) =: V(Q, P),$$

where $V(Q, P)$ is the *variational distance.*

If we take $f : [0, \infty) \to \mathbb{R}$, $f(t) = t^2 - 1$ for $t \geq 0$ then for Q, $P \in S_1(\mathcal{M})$ with P invertible we have

$$S_f(Q, P) = \operatorname{tr}\left(Q^2 P^{-1}\right) - 1 =: \chi^2(Q, P),$$

which is called the χ^2-*distance*

Let $q \in (0,1)$ and define the convex function $f_q : [0,\infty) \to \mathbb{R}$ by $f_q(t) = \frac{1-t^q}{1-q}$. Then

$$S_{f_q}(Q,P) = \frac{1 - \operatorname{tr}\left(Q^q P^{1-q}\right)}{1-q},$$

which is *Tsallis relative entropy.*

If we consider the convex function $f : [0,\infty) \to \mathbb{R}$ by $f(t) = \frac{1}{2}\left(\sqrt{t} - 1\right)^2$, then

$$S_f(Q,P) = 1 - \operatorname{tr}\left(Q^{1/2} P^{1/2}\right) =: h^2(Q,P),$$

which is known as *Hellinger discrimination.*

If we take $f : (0,\infty) \to \mathbb{R}$, $f(t) = -\ln t$ then for Q, $P \in S_1(\mathcal{M})$ and Q, P invertible we have

$$S_f(Q,P) = \operatorname{tr}\left[P(\ln P - \ln Q)\right] = U(P,Q).$$

The reader can obtain other particular quantum f-divergence measures by utilizing the normalized convex functions from Introduction, namely the convex functions defining the dichotomy class, Matsushita's divergences, Puri-Vincze divergences or divergences of Arimoto-type. We omit the details.

In the important case of finite dimensional spaces and the generalized inverse P^{-1}, numerous properties of the quantum f-divergence, mostly in the case when f is *operator convex,* have been obtained in the recent papers [17], [18], [22]- [25] and the references therein.

In what follows we obtain several inequalities for the larger class of convex functions on an interval.

3. Inequalities for f Convex and Normalized

Suppose that I is an interval of real numbers with interior $\mathring{I}$ and $f : I \to \mathbb{R}$ is a convex function on I. Then f is continuous on $\mathring{I}$ and has finite left and right derivatives at each point of $\mathring{I}$. Moreover, if $x, y \in \mathring{I}$ and $x < y$, then $f'_-(x) \le f'_+(x) \le f'_-(y) \le f'_+(y)$, which shows that both f'_- and f'_+ are nondecreasing function on $\mathring{I}$. It is also known that a convex function must be differentiable except for at most countably many points.

For a convex function $f : I \to \mathbb{R}$, the subdifferential of f denoted by ∂f is the set of all functions $\varphi : I \to [-\infty, \infty]$ such that $\varphi\left(\mathring{I}\right) \subset \mathbb{R}$ and

$$\text{(G)} \qquad f(x) \geq f(a) + (x-a)\varphi(a) \text{ for any } x, a \in I.$$

It is also well known that if f is convex on I, then ∂f is nonempty, f'_-, $f'_+ \in \partial f$ and if $\varphi \in \partial f$, then

$$f'_-(x) \leq \varphi(x) \leq f'_+(x) \text{ for any } x \in \mathring{I}.$$

In particular, φ is a nondecreasing function.

If f is differentiable and convex on $\mathring{I}$, then $\partial f = \{f'\}$.

We are able now to state and prove the first result concerning the quantum f-divergence for the general case of convex functions.

Theorem 4. *Let $f : [0, \infty) \to \mathbb{R}$ be a continuous convex function that is normalized, i.e. $f(1) = 0$. Then for any Q, $P \in S_1(\mathcal{M})$, with P invertible, we have*

$$0 \leq S_f(Q, P). \tag{3.1}$$

Moreover, if f is continuously differentiable, then also

$$S_f(Q, P) \leq S_{\ell f'}(Q, P) - S_{f'}(Q, P), \tag{3.2}$$

where the function ℓ is defined as $\ell(t) = t$, $t \in \mathbb{R}$.

Proof. Since f is convex and normalized, then by the gradient inequality (G) we have

$$f(t) \geq (t-1) f'_+(1)$$

for $t > 0$.

Applying the property (P) for the operator $\mathfrak{A}_{Q,P}$, then we have for any $T \in \mathcal{M}$

$$\begin{aligned} \langle f(\mathfrak{A}_{Q,P}) T, T\rangle_2 &\geq f'_+(1) \left\langle \left(\mathfrak{A}_{Q,P} - 1_{\mathcal{B}_2(H)}\right) T, T\right\rangle_2 \\ &= f'_+(1) \left[\langle \mathfrak{A}_{Q,P} T, T\rangle_2 - \|T\|_2\right], \end{aligned}$$

which, in terms of trace, can be written as

$$\operatorname{tr}(T^* f(\mathfrak{A}_{Q,P}) T) \geq f'_+(1) \left[\operatorname{tr}\left(\left|Q^{1/2} T P^{-1/2}\right|^2\right) - \operatorname{tr}\left(|T|^2\right)\right] \tag{3.3}$$

for any $T \in \mathcal{M}$.

Now, if we take in (3.3) $T = P^{1/2}$ where $P \in S_1(\mathcal{M})$, with P invertible, then we get

$$S_f(Q, P) \geq f'_+(1) [\operatorname{tr}(Q) - \operatorname{tr}(P)] = 0$$

and the inequality (3.1) is proved.

Further, if f is continuously differentiable, then by the gradient inequality we also have

$$(t-1) f'(t) \geq f(t)$$

for $t > 0$.

Applying the property (P) for the operator $\mathfrak{A}_{Q,P}$, then we have for any $T \in \mathcal{M}$

$$\left\langle \left(\mathfrak{A}_{Q,P} - 1_{\mathcal{B}_2(H)}\right) f'(\mathfrak{A}_{Q,P}) T, T\right\rangle_2 \geq \langle f(\mathfrak{A}_{Q,P}) T, T\rangle_2 ,$$

namely

$$\langle \mathfrak{A}_{Q,P} f'(\mathfrak{A}_{Q,P}) T, T\rangle_2 - \langle f'(\mathfrak{A}_{Q,P}) T, T\rangle_2 \geq \langle f(\mathfrak{A}_{Q,P}) T, T\rangle_2 ,$$

for any $T \in \mathcal{M}$, or in terms of trace

$$\operatorname{tr}(T^* \mathfrak{A}_{Q,P} f'(\mathfrak{A}_{Q,P}) T) - \operatorname{tr}(T^* f'(\mathfrak{A}_{Q,P}) T) \geq \operatorname{tr}(T^* f(\mathfrak{A}_{Q,P}) T), \tag{3.4}$$

for any $T \in \mathcal{M}$.

If in (3.4) we take $T = P^{1/2}$, where $P \in S_1(\mathcal{M})$, with P invertible, then we get the desired result (3.2). □

Remark 2. If we take in (3.2) $f : (0, \infty) \to \mathbb{R}$, $f(t) = -\ln t$ then for Q, $P \in S_1(\mathcal{M})$ and Q, P invertible we have

$$0 \leq U(P,Q) \leq \chi^2(P,Q). \tag{3.5}$$

We need the following lemma.

Lemma 1. *Let S be a selfadjoint operator on the Hilbert space $(H, \langle\cdot,\cdot\rangle)$ and with spectrum $\operatorname{Sp}(S) \subseteq [\gamma, \Gamma]$ for some real numbers γ, Γ. If $g : [\gamma, \Gamma] \to \mathbb{C}$ is a continuous function such that*

$$|g(t) - \lambda| \leq \rho \text{ for any } t \in [\gamma, \Gamma] \tag{3.6}$$

for some complex number $\lambda \in \mathbb{C}$ and positive number ρ, then

$$\begin{aligned} |\langle Sg(S)x, x\rangle - \langle Sx, x\rangle \langle g(S)x, x\rangle| &\leq \rho \langle |S - \langle Sx, x\rangle 1_H| x, x\rangle \\ &\leq \rho \left[\left\langle S^2 x, x\right\rangle - \langle Sx, x\rangle^2\right]^{1/2} \end{aligned} \tag{3.7}$$

for any $x \in H$, $\|x\| = 1$.

Proof. We observe that

$$\langle Sg(S)x, x\rangle - \langle Sx, x\rangle \langle g(S)x, x\rangle = \langle (S - \langle Sx, x\rangle 1_H)(g(S) - \lambda 1_H) x, x\rangle \tag{3.8}$$

for any $x \in H$, $\|x\| = 1$.

For any selfadjoint operator B we have the modulus inequality

$$|\langle Bx,x\rangle| \le \langle |B|\,x,x\rangle \text{ for any } x\in H, \|x\|=1. \tag{3.9}$$

Also, utilizing the continuous functional calculus we have for each fixed $x\in H, \|x\|=1$

$$\begin{aligned}|(S-\langle Sx,x\rangle 1_H)(g(S)-\lambda 1_H)| &= |S-\langle Sx,x\rangle 1_H|\,|g(S)-\lambda 1_H|\\ &\le \rho\,|S-\langle Sx,x\rangle 1_H|,\end{aligned}$$

which implies that

$$\langle |(S-\langle Sx,x\rangle 1_H)(g(S)-\lambda 1_H)|\,x,x\rangle \le \rho\,\langle |S-\langle Sx,x\rangle 1_H|\,x,x\rangle \tag{3.10}$$

for any $x\in H, \|x\|=1$.

Therefore, by taking the modulus in (3.8) and utilizing (3.9) and (3.10) we get

$$\begin{aligned}&|\langle Sg(S)x,x\rangle-\langle Sx,x\rangle\langle g(S)x,x\rangle|\\ &=|\langle (S-\langle Sx,x\rangle 1_H)(g(S)-\lambda 1_H)x,x\rangle|\\ &\le \langle |(S-\langle Sx,x\rangle 1_H)(g(S)-\lambda 1_H)|\,x,x\rangle\\ &\le \rho\,\langle |S-\langle Sx,x\rangle 1_H|\,x,x\rangle\end{aligned} \tag{3.11}$$

for any $x\in H, \|x\|=1$, which proves the first inequality in (3.7).

Using Schwarz inequality we also have

$$\begin{aligned}\langle |S-\langle Sx,x\rangle 1_H|\,x,x\rangle &\le \left\langle (S-\langle Sx,x\rangle 1_H)^2 x,x\right\rangle^{1/2}\\ &=\left[\left\langle S^2x,x\right\rangle-\langle Sx,x\rangle^2\right]^{1/2}\end{aligned}$$

for any $x\in H, \|x\|=1$, and the lemma is proved. □

Corollary 1. *With the assumption of Lemma 1, we have*

$$\begin{aligned}0 &\le \left\langle S^2x,x\right\rangle-\langle Sx,x\rangle^2 \le \frac{1}{2}(\Gamma-\gamma)\,\langle |S-\langle Sx,x\rangle 1_H|\,x,x\rangle\\ &\le \frac{1}{2}(\Gamma-\gamma)\left[\left\langle S^2x,x\right\rangle-\langle Sx,x\rangle^2\right]^{1/2} \le \frac{1}{4}(\Gamma-\gamma)^2,\end{aligned} \tag{3.12}$$

for any $x\in H$, $\|x\|=1$.

Proof. If we take in Lemma 1 $g(t) = t$, $\lambda = \frac{1}{2}(\Gamma + \gamma)$ and $\rho = \frac{1}{2}(\Gamma - \gamma)$, then we get

$$0 \le \langle S^2 x, x\rangle - \langle Sx, x\rangle^2 \le \frac{1}{2}(\Gamma - \gamma)\langle |S - \langle Sx, x\rangle 1_H| x, x\rangle \le \frac{1}{2}(\Gamma - \gamma)\left[\langle S^2 x, x\rangle - \langle Sx, x\rangle^2\right]^{1/2} \tag{3.13}$$

for any $x \in H$, $\|x\| = 1$.

From the first and last terms in (3.13) we have

$$\left[\langle S^2 x, x\rangle - \langle Sx, x\rangle^2\right]^{1/2} \le \frac{1}{2}(\Gamma - \gamma),$$

which proves the rest of (3.12). □

We can prove the following result that provides simpler upper bounds for the quantum f-divergence when the operators P and Q satisfy the condition (2.2).

THEOREM 5. *Let $f : [0, \infty) \to \mathbb{R}$ be a continuous convex function that is normalized. If Q, $P \in S_1(\mathcal{M})$, with P invertible, and there exists $R \ge 1 \ge r \ge 0$ such that*

$$r \operatorname{tr}\left(|T|^2\right) \le \operatorname{tr}\left(\left|Q^{1/2} T P^{-1/2}\right|^2\right) \le R \operatorname{tr}\left(|T|^2\right) \tag{3.14}$$

for any $T \in \mathcal{M}$, then

$$0 \le S_f(Q, P) \le \frac{1}{2}\left[f'_-(R) - f'_+(r)\right] V(Q, P) \le \frac{1}{2}\left[f'_-(R) - f'_+(r)\right] \chi(Q, P) \le \frac{1}{4}(R - r)\left[f'_-(R) - f'_+(r)\right]. \tag{3.15}$$

Proof. Without loosing the generality, we prove the inequality in the case that f is continuously differentiable on $(0, \infty)$.

Since f' is monotonic nondecreasing on $[r, R]$ we have that

$$f'(r) \le f'(t) \le f'(R) \text{ for any } t \in [r, R],$$

which implies that

$$\left| f'(t) - \frac{f'(R) + f'(r)}{2} \right| \le \frac{1}{2}\left[f'(R) - f'(r)\right]$$

for any $t \in [r, R]$.

Applying Lemma 1 and Corollary 1 in the Hilbert space $(\mathcal{M}, \langle\cdot,\cdot\rangle_2)$ and for the selfadjoint operator $\mathfrak{A}_{Q,P}$ we have

$$\begin{aligned}
&\left|\langle \mathfrak{A}_{Q,P} f'(\mathfrak{A}_{Q,P}) T, T\rangle_2 - \langle \mathfrak{A}_{Q,P} T, T\rangle_2 \langle f'(\mathfrak{A}_{Q,P}) T, T\rangle_2\right| \\
&\leq \frac{1}{2}[f'(R) - f'(r)] \left\langle \left|\mathfrak{A}_{Q,P} - \langle \mathfrak{A}_{Q,P} T, T\rangle_2 1_{\mathcal{B}_2(H)}\right| T, T\right\rangle_2 \\
&\leq \frac{1}{2}[f'(R) - f'(r)] \left[\left\langle \mathfrak{A}_{Q,P}^2 T, T\right\rangle_2 - \langle \mathfrak{A}_{Q,P} T, T\rangle_2^2\right]^{1/2} \\
&\leq \frac{1}{4}(R-r)\left[f'_-(R) - f'_+(r)\right]
\end{aligned}$$

for any $T \in \mathcal{M}$, $\|T\|_2 = 1$.

If in this inequality we take $T = P^{1/2}$, $P \in S_1(\mathcal{M})$, with P invertible, then we get

$$\begin{aligned}
&\left|\left\langle \mathfrak{A}_{Q,P} f'(\mathfrak{A}_{Q,P}) P^{1/2}, P^{1/2}\right\rangle_2 - \left\langle f'(\mathfrak{A}_{Q,P}) P^{1/2}, P^{1/2}\right\rangle_2\right| \\
&\leq \frac{1}{2}[f'(R) - f'(r)] \left\langle \left|\mathfrak{A}_{Q,P} - \left\langle \mathfrak{A}_{Q,P} P^{1/2}, P^{1/2}\right\rangle_2 1_{\mathcal{B}_2(H)}\right| P^{1/2}, P^{1/2}\right\rangle_2 \\
&\leq \frac{1}{2}[f'(R) - f'(r)] \left[\left\langle \mathfrak{A}_{Q,P}^2 P^{1/2}, P^{1/2}\right\rangle_2 - \left\langle \mathfrak{A}_{Q,P} P^{1/2}, P^{1/2}\right\rangle_2^2\right]^{1/2} \\
&\leq \frac{1}{4}(R-r)\left[f'_-(R) - f'_+(r)\right],
\end{aligned}$$

which can be written as

$$\begin{aligned}
|S_{\ell f'}(Q,P) - S_{f'}(Q,P)| &\leq \frac{1}{2}\left[f'_-(R) - f'_+(r)\right] V(Q,P) \\
&\leq \frac{1}{2}\left[f'_-(R) - f'_+(r)\right] \chi(Q,P) \\
&\leq \frac{1}{4}(R-r)\left[f'_-(R) - f'_+(r)\right].
\end{aligned}$$

Making use of Theorem 4 we deduce the desired result (3.15). □

REMARK 3. If we take in (3.15) $f(t) = t^2 - 1$, then we get

$$\begin{aligned}
0 &\leq \chi^2(Q,P) \leq \frac{1}{2}(R-r) V(Q,P) \leq \frac{1}{2}(R-r)\chi(Q,P) \\
&\leq \frac{1}{4}(R-r)^2
\end{aligned} \tag{3.16}$$

for Q, $P \in S_1(\mathcal{M})$, with P invertible and satisfying the condition (3.14).

If we take in (3.15) $f(t) = t\ln t$, then we get the inequality

$$0 \le U(Q,P) \le \frac{1}{2}\ln\left(\frac{R}{r}\right) V(Q,P) \le \frac{1}{2}\ln\left(\frac{R}{r}\right)\chi(Q,P) \le \frac{1}{4}(R-r)\ln\left(\frac{R}{r}\right) \tag{3.17}$$

provided that $Q,\ P \in S_1(H)$, with $P,\ Q$ invertible and satisfying the condition (3.14).

With the same conditions and if we take $f(t) = -\ln t$, then

$$0 \le U(P,Q) \le \frac{R-r}{2rR} V(Q,P) \le \frac{R-r}{2rR}\chi(Q,P) \le \frac{(R-r)^2}{4rR}. \tag{3.18}$$

If we take in (3.15) $f(t) = f_q(t) = \frac{1-t^q}{1-q}$, then we get

$$\begin{aligned} 0 \le S_{f_q}(Q,P) &\le \frac{q}{2(1-q)}\left(\frac{R^{1-q}-r^{1-q}}{R^{1-q}r^{1-q}}\right) V(Q,P) \\ &\le \frac{q}{2(1-q)}\left(\frac{R^{1-q}-r^{1-q}}{R^{1-q}r^{1-q}}\right)\chi(Q,P) \\ &\le \frac{q}{4(1-q)}\left(\frac{R^{1-q}-r^{1-q}}{R^{1-q}r^{1-q}}\right)(R-r) \end{aligned} \tag{3.19}$$

provided that $Q,\ P \in S_1(\mathcal{M})$, with $P,\ Q$ invertible and satisfying the condition (3.14).

4. Other Reverse Inequalities

Utilising different techniques we can obtain other upper bounds for the quantum f-divergence as follows. Applications for Umegaki relative entropy and χ^2-divergence are also provided.

Theorem 6. *Let $f : [0,\infty) \to \mathbb{R}$ be a continuous convex function that is normalized. If $Q,\ P \in S_1(\mathcal{M})$, with P invertible, and there exists $R \ge 1 \ge r \ge 0$ such that the condition (3.14) is satisfied, then*

$$0 \le S_f(Q,P) \le \frac{(R-1)f(r) + (1-r)f(R)}{R-r}. \tag{4.1}$$

Proof. By the convexity of f we have

$$f(t) = f\left(\frac{(R-t)r + (t-r)R}{R-r}\right) \le \frac{(R-t)f(r) + (t-r)f(R)}{R-r}$$

for any $t \in [r, R]$.

This inequality implies the following inequality in the operator order of $\mathcal{B}(\mathcal{M})$

$$f(\mathfrak{A}_{Q,P}) \leq \frac{(R1_{\mathcal{M}} - \mathfrak{A}_{Q,P}) f(r) + (\mathfrak{A}_{Q,P} - r1_{\mathcal{M}}) f(R)}{R - r},$$

which can be written as

$$\begin{aligned} (4.2) \quad & \langle f(\mathfrak{A}_{Q,P}) T, T \rangle_2 \\ & \leq \frac{f(r)}{R - r} \langle (R1_{\mathcal{M}} - \mathfrak{A}_{Q,P}) T, T \rangle_2 + \frac{f(R)}{R - r} \langle (\mathfrak{A}_{Q,P} - r1_{\mathcal{M}}) T, T \rangle_2 \end{aligned}$$

for any $T \in \mathcal{M}$.

Now, if we take in (4.2) $T = P^{1/2}$, $P \in S_1(\mathcal{M})$, then we get the desired result (4.2). □

Remark 4. If we take in (4.1) $f(t) = t^2 - 1$, then we get

$$(4.3) \qquad 0 \leq \chi^2(Q, P) \leq (R - 1)(1 - r) \frac{R + r + 2}{R - r}$$

for Q, $P \in S_1(\mathcal{M})$, with P invertible and satisfying the condition (3.14).

If we take in (4.1) $f(t) = t \ln t$, then we get the inequality

$$(4.4) \qquad 0 \leq U(Q, P) \leq \ln \left[r^{\frac{(R-1)r}{R-r}} R^{\frac{R(1-r)}{R-r}} \right]$$

provided that Q, $P \in S_1(\mathcal{M})$, with P, Q invertible and satisfying the condition (3.14).

If we take in (4.1) $f(t) = -\ln t$, then we get the inequality

$$(4.5) \qquad 0 \leq U(P, Q) \leq \ln \left[r^{\frac{1-R}{R-r}} R^{\frac{r-1}{R-r}} \right]$$

for Q, $P \in S_1(\mathcal{M})$, with P, Q invertible and satisfying the condition (3.14).

We also have:

Theorem 7. *Let $f : [0, \infty) \to \mathbb{R}$ be a continuous convex function that is normalized. If Q, $P \in S_1(\mathcal{M})$, with P invertible, and there* *exists $R > 1 > r \geq 0$ such that the condition (3.14) is satisfied, then*

$$0 \leq S_f(Q,P) \leq \frac{(R-1)(1-r)}{R-r}\Psi_f(1;r,R) \tag{4.6}$$
$$\leq \frac{(R-1)(1-r)}{R-r}\sup_{t\in(r,R)}\Psi_f(t;r,R)$$
$$\leq (R-1)(1-r)\frac{f'_-(R)-f'_+(r)}{R-r}$$
$$\leq \frac{1}{4}(R-r)\left[f'_-(R)-f'_+(r)\right]$$

where $\Psi_f(\cdot;r,R):(r,R)\to\mathbb{R}$ is defined by

$$\Psi_f(t;r,R) = \frac{f(R)-f(t)}{R-t} - \frac{f(t)-f(r)}{t-r}. \tag{4.7}$$

We also have

$$0 \leq S_f(Q,P) \leq \frac{(R-1)(1-r)}{R-r}\Psi_f(1;r,R) \tag{4.8}$$
$$\leq \frac{1}{4}(R-r)\Psi_f(1;r,R)$$
$$\leq \frac{1}{4}(R-r)\sup_{t\in(r,R)}\Psi_f(t;r,R)$$
$$\leq \frac{1}{4}(R-r)\left[f'_-(R)-f'_+(r)\right].$$

Proof. By denoting

$$\Delta_f(t;r,R) := \frac{(t-r)f(R)+(R-t)f(r)}{R-r} - f(t), \quad t\in[r,R]$$

we have

$$\Delta_f(t;r,R) = \frac{(t-r)f(R)+(R-t)f(r)-(R-r)f(t)}{R-r} \tag{4.9}$$
$$= \frac{(t-r)f(R)+(R-t)f(r)-(T-t+t-r)f(t)}{R-r}$$
$$= \frac{(t-r)[f(R)-f(t)]-(R-t)[f(t)-f(r)]}{M-m}$$
$$= \frac{(R-t)(t-r)}{R-r}\Psi_f(t;r,R)$$

for any $t\in(r,R)$.

From the proof of Theorem 6 we have

$$(4.10)\quad \begin{aligned} &\langle f(\mathfrak{A}_{Q,P})T,T\rangle_2 \\ &\leq \frac{f(r)}{R-r}\langle (R1_{\mathcal{M}}-\mathfrak{A}_{Q,P})T,T\rangle_2 + \frac{f(R)}{R-r}\langle (\mathfrak{A}_{Q,P}-r1_{\mathcal{M}})T,T\rangle_2 \\ &= \frac{\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2 - r\right)f(R) + \left(R-\langle \mathfrak{A}_{Q,P}T,T\rangle_2\right)f(r)}{R-r} \end{aligned}$$

for any $T \in \mathcal{M}$, $\|T\|_2 = 1$.

This implies that

(4.11)

$$\begin{aligned} 0 &\leq \langle f(\mathfrak{A}_{Q,P})T,T\rangle_2 - f\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2\right) \\ &\leq \frac{\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2 - r\right)f(R) + \left(R-\langle \mathfrak{A}_{Q,P}T,T\rangle_2\right)f(r)}{R-r} - f\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2\right) \\ &= \Delta_f\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2 ; r, R\right) \\ &= \frac{\left(R-\langle \mathfrak{A}_{Q,P}T,T\rangle_2\right)\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2 - r\right)}{R-r}\Psi_f\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2 ; r, R\right) \end{aligned}$$

for any $T \in \mathcal{M}$, $\|T\|_2 = 1$.

Since

(4.12)

$$\begin{aligned} \Psi_f\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2 ; r, R\right) &\leq \sup_{t\in(r,R)} \Psi_f(t;r,R) \\ &= \sup_{t\in(r,R)}\left[\frac{f(R)-f(t)}{R-t} - \frac{f(t)-f(r)}{t-r}\right] \\ &\leq \sup_{t\in(r,R)}\left[\frac{f(R)-f(t)}{R-t}\right] + \sup_{t\in(r,R)}\left[-\frac{f(t)-f(r)}{t-r}\right] \\ &= \sup_{t\in(r,R)}\left[\frac{f(R)-f(t)}{R-t}\right] - \inf_{t\in(r,R)}\left[\frac{f(t)-f(r)}{t-r}\right] \\ &= f'_-(R) - f'_+(r), \end{aligned}$$

and, obviously

$$(4.13)\quad \frac{1}{R-r}\left(R-\langle \mathfrak{A}_{Q,P}T,T\rangle_2\right)\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2 - r\right) \leq \frac{1}{4}(R-r),$$

then by (4.11)-(4.13) we have

(4.14)

$$\begin{aligned}0 &\le \langle f(\mathfrak{A}_{Q,P})T,T\rangle_2 - f\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2\right)\\ &\le \frac{\left(R-\langle \mathfrak{A}_{Q,P}T,T\rangle_2\right)\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2 - r\right)}{R-r}\Psi_f\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2; r,R\right)\\ &\le \frac{\left(R-\langle \mathfrak{A}_{Q,P}T,T\rangle_2\right)\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2 - r\right)}{R-r}\sup_{t\in(r,R)}\Psi_f(t;r,R)\\ &\le \left(R-\langle \mathfrak{A}_{Q,P}T,T\rangle_2\right)\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2 - r\right)\frac{f'_-(R)-f'_+(r)}{R-r}\\ &\le \frac{1}{4}(R-r)\left[f'_-(R)-f'_+(r)\right]\end{aligned}$$

for any $T \in \mathcal{M}$, $\|T\|_2 = 1$.

Now, if we take in (4.14) $T = P^{1/2}$, then we get the desired result (4.6).

The inequality (4.8) is obvious from (4.6). □

Remark 5. If we consider the convex normalized function $f(t) = t^2 - 1$, then

$$\Psi_f(t;r,R) = \frac{R^2-t^2}{R-t} - \frac{t^2-r^2}{t-r} = R-r,\ t\in(r,R)$$

and we get from (4.6) the simple inequality

$$0 \le \chi^2(Q,P) \le (R-1)(1-r) \tag{4.15}$$

for $Q, P \in S_1(\mathcal{M})$, with P invertible and satisfying the condition (3.14), which is better than (4.3).

If we take the convex normalized function $f(t) = t^{-1} - 1$, then we have

$$\Psi_f(t;r,R) = \frac{R^{-1}-t^{-1}}{R-t} - \frac{t^{-1}-r^{-1}}{t-r} = \frac{R-r}{rRt},\ t\in[r,R].$$

Also

$$S_f(Q,P) = \chi^2(P,Q).$$

Using (4.6) we get

$$0 \le \chi^2(P,Q) \le \frac{(R-1)(1-r)}{Rr} \tag{4.16}$$

for $Q, P \in S_1(\mathcal{M})$, with Q invertible and satisfying the condition (3.14).

If we consider the convex function $f(t) = -\ln t$ defined on $[r, R] \subset (0, \infty)$, then

$$\begin{aligned}\Psi_f(t; r, R) &= \frac{-\ln R + \ln t}{R - t} - \frac{-\ln t + \ln r}{t - r} \\ &= \frac{(R - r)\ln t - (R - t)\ln r - (t - r)\ln R}{(M - t)(t - m)} \\ &= \ln\left(\frac{t^{R-r}}{r^{R-t}M^{t-r}}\right)^{\frac{1}{(R-t)(t-r)}},\ t \in (r, R).\end{aligned}$$

Then by (4.6) we have

$$0 \le U(P, Q) \le \ln\left[r^{\frac{1-R}{R-r}}R^{\frac{r-1}{R-r}}\right] \le \frac{(R-1)(1-r)}{rR} \tag{4.17}$$

for Q, $P \in S_1(\mathcal{M})$, with P, Q invertible and satisfying the condition (3.14).

We also have:

Theorem 8. *Let $f : [0, \infty) \to \mathbb{R}$ be a continuous convex function that is normalized. If $Q, P \in S_1(\mathcal{M})$, with P invertible, and there exists $R > 1 > r \ge 0$ such that the condition (3.14) is satisfied, then*

$$0 \le S_f(Q, P) \le 2\left[\frac{f(r) + f(R)}{2} - f\left(\frac{r + R}{2}\right)\right]. \tag{4.18}$$

Proof. We recall the following result (see for instance [4]) that provides a refinement and a reverse for the weighted Jensen's discrete inequality:

$$\begin{aligned}&n \min_{i\in\{1,\dots,n\}}\{p_i\}\left[\frac{1}{n}\sum_{i=1}^n f(x_i) - f\left(\frac{1}{n}\sum_{i=1}^n x_i\right)\right] \\ &\le \frac{1}{P_n}\sum_{i=1}^n p_i f(x_i) - f\left(\frac{1}{P_n}\sum_{i=1}^n p_i x_i\right) \\ &\le n \max_{i\in\{1,\dots,n\}}\{p_i\}\left[\frac{1}{n}\sum_{i=1}^n f(x_i) - f\left(\frac{1}{n}\sum_{i=1}^n x_i\right)\right],\end{aligned} \tag{4.19}$$

where $f : C \to \mathbb{R}$ is a convex function defined on the convex subset C of the linear space X, $\{x_i\}_{i\in\{1,\dots,n\}} \subset C$ are vectors and $\{p_i\}_{i\in\{1,\dots,n\}}$ are nonnegative numbers with $P_n := \sum_{i=1}^n p_i > 0$.

For $n = 2$ we deduce from (3.6) that

$$
\begin{aligned}
(4.20)\qquad & 2\min\{s, 1-s\}\left[\frac{f(x)+f(y)}{2} - f\left(\frac{x+y}{2}\right)\right] \\
& \leq sf(x) + (1-s) f(y) - f(sx + (1-s)y) \\
& \leq 2\max\{s, 1-s\}\left[\frac{f(x)+f(y)}{2} - f\left(\frac{x+y}{2}\right)\right]
\end{aligned}
$$

for any $x, y \in C$ and $s \in [0,1]$.

Now, if we use the second inequality in (4.20) for $x = r$, $y = R$, $s = \frac{R-t}{R-r}$ with $t \in [r, R]$, then we have

$$
\begin{aligned}
(4.21)\qquad & \frac{(R-t) f(r) + (t-r) f(R)}{R-r} - f(t) \\
& \leq 2\max\left\{\frac{R-t}{R-r}, \frac{t-r}{R-r}\right\}\left[\frac{f(r)+f(R)}{2} - f\left(\frac{r+R}{2}\right)\right] \\
& = \left[1 + \frac{2}{R-r}\left|t - \frac{r+R}{2}\right|\right]\left[\frac{f(r)+f(R)}{2} - f\left(\frac{r+R}{2}\right)\right]
\end{aligned}
$$

for any $t \in [r, R]$.

This implies in the operator order of $\mathcal{B}(\mathcal{M})$

$$
\begin{aligned}
& \frac{(R1_{\mathcal{M}} - \mathfrak{A}_{Q,P}) f(r) + (\mathfrak{A}_{Q,P} - r1_{\mathcal{M}}) f(R)}{R-r} - f(\mathfrak{A}_{Q,P}) \\
& \leq \left[\frac{f(r)+f(R)}{2} - f\left(\frac{r+R}{2}\right)\right] \\
& \times \left[1_{\mathcal{M}} + \frac{2}{R-r}\left|\mathfrak{A}_{Q,P} - \frac{r+R}{2}1_{\mathcal{M}}\right|\right]
\end{aligned}
$$

which implies that

(4.22)

$$\begin{aligned}
0 &\le \langle f(\mathfrak{A}_{Q,P})T,T\rangle_2 - f\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2\right) \\
&\le \frac{\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2 - r\right) f(R) + \left(R - \langle \mathfrak{A}_{Q,P}T,T\rangle_2\right) f(r)}{R-r} - f\left(\langle \mathfrak{A}_{Q,P}T,T\rangle_2\right) \\
&\le \left[\frac{f(r)+f(R)}{2} - f\left(\frac{r+R}{2}\right)\right] \\
&\times \left[1 + \frac{2}{R-r}\left\langle \left|\mathfrak{A}_{Q,P} - \frac{r+R}{2}1_{\mathcal{M}}\right| T,T\right\rangle_2\right] \\
&\le 2\left[\frac{f(r)+f(R)}{2} - f\left(\frac{r+R}{2}\right)\right]
\end{aligned}$$

for any $T \in \mathcal{M}$, $\|T\|_2 = 1$.

If we take in (4.22) $T = P^{1/2}$, $P \in S_1(\mathcal{M})$, then we get the desired result (4.18). □

REMARK 6. If we take $f(t) = t^2 - 1$ in (4.18), then we get

$$0 \le \chi^2(Q,P) \le \frac{1}{2}(R-r)^2$$

for $Q, P \in S_1(\mathcal{M})$, with P invertible and satisfying the condition (3.14), which is not as good as (4.15).

If we take in (4.18) $f(t) = t^{-1} - 1$, then we have

$$0 \le \chi^2(P,Q) \le \frac{(R-r)^2}{rR(r+R)} \tag{4.23}$$

for $Q, P \in S_1(\mathcal{M})$, with P invertible and satisfying the condition (3.14).

If we take in (4.18) $f(t) = -\ln t$, then we have

$$0 \le U(P,Q) \le \ln\left(\frac{(R+r)^2}{4rR}\right) \tag{4.24}$$

for $Q, P \in S_1(\mathcal{M})$, with P invertible and satisfying the condition (3.14).

From (3.18) we have the following absolute upper bound

$$0 \le U(P,Q) \le \frac{(R-r)^2}{4rR} \tag{4.25}$$

for $Q, P \in S_1(\mathcal{M})$, with P invertible and satisfying the condition (3.14).

Utilising the elementary inequality $\ln x \le x - 1$, $x > 0$, we have that

$$\ln\left(\frac{(R+r)^2}{4rR}\right) \le \frac{(R-r)^2}{4rR},$$

which shows that (4.24) is better than (4.25).

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