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This is the In Press version of the following publication

Taghavi, A, Darvish, Vahid, Nazari, HM and Dragomir, Sever S (2015) Some results on singular value inequalities of compact operators in Hilbert space. arXiv. (In Press)

The publisher's official version can be found at
<http://arxiv.org/abs/1510.00114>

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SOME RESULTS ON SINGULAR VALUE INEQUALITIES OF COMPACT OPERATORS IN HILBERT SPACE

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ABSTRACT. We prove several singular value inequalities for sum and product of compact operators in Hilbert space. Some of our results generalize the previous inequalities for operators. Also, applications of some inequalities are given.

1. Introduction

Let $B(H)$ stand for the C^* -algebra of all bounded linear operators on a complex separable Hilbert space H with inner product $\langle \cdot, \cdot \rangle$ and let $K(H)$ denote the two-sided ideal of compact operators in $B(H)$. For $A \in B(H)$, let $\|A\| = \sup\{\|Ax\| : \|x\| = 1\}$ denote the usual operator norm of A and $|A| = (A^*A)^{1/2}$ be the absolute value of A .

An operator $A \in B(H)$ is positive and write $A \geq 0$ if $\langle Ax, x \rangle \geq 0$ for all $x \in H$. We say $A \leq B$ whenever $B - A \geq 0$.

We consider the wide class of unitarily invariant norms $||| \cdot |||$. Each of these norms is defined on an ideal in $B(H)$ and it will be implicitly understood that when we talk of $|||T|||$, then the operator T belongs to the norm ideal associated with $||| \cdot |||$. Each unitarily invariant norm $||| \cdot |||$ is characterized by the invariance property $|||UTV||| = |||T|||$ for all operators T in the norm ideal associated with $||| \cdot |||$ and for all unitary operators U and V in $B(H)$. For $1 \leq p < \infty$, the Schatten p -norm of a compact operator A is defined by $\|A\|_p = (\text{tr } |A|^p)^{1/p}$, where tr is the usual trace functional. Note that for $A \in K(H)$ we have, $\|A\| = s_1(A)$, and if A is a Hilbert-Schmidt operator, then $\|A\|_2 = (\sum_{j=1}^{\infty} s_j^2(A))^{1/2}$. These norms are special examples of the more general class of the Schatten p -norms, which are unitarily invariant [2].

2010 *Mathematics Subject Classification.* 15A60, 47A30, 47B05, 47B10.

Key words and phrases. Singular value, compact operator, normal operator, unitarily invariant norm, Schatten p -norm.

The direct sum $A \oplus B$ denotes the block diagonal matrix $\begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}$ defined on $H \oplus H$, see [1, 9]. It is easy to see that

$$(1.1) \quad \|A \oplus B\| = \max(\|A\|, \|B\|),$$

and

$$(1.2) \quad \|A \oplus B\|_p = (\|A\|_p^p + \|B\|_p^p)^{1/p}.$$

We denote the singular values of an operator $A \in K(H)$ as $s_1(A) \geq s_2(A) \geq \dots$ are the eigenvalues of the positive operator $|A| = (A^*A)^{1/2}$ and eigenvalues of the self-adjoint operator A denote as $\lambda_1 \geq \lambda_2 \geq \dots$ which repeated accordingly to multiplicity.

There is a one-to-one correspondence between symmetric gauge functions defined on sequences of real numbers and unitarily invariant norms defined on norm ideals of operators. More precisely, if $\|\cdot\|$ is unitarily invariant norm, then there exists a unique symmetric gauge function Φ such that

$$\|\|A\|\| = \Phi(s_1(A), s_2(A), \dots),$$

for every operator $A \in K(H)$. Let $A \in K(H)$, and if $U, V \in B(H)$ are unitarily operators, then

$$s_j(UAV) = s_j(A),$$

for $j = 1, 2, \dots$ and so unitarily invariant norms satisfies the invariance property

$$\|\|UAV\|\| = \|\|A\|\|.$$

In this paper, we obtain some inequalities for sum and product of operators. Some of our results generalize the previous inequalities for operators.

2. Some singular value inequalities for sum and product of operators

In this section we give inequalities for singular value of operators. Also, some norm inequalities are obtained as an application.

First we should remind the following inequalities. We apply inequalities (2.1) and (2.3) in our proofs.

The following inequality due to Tao [8] asserts that if $A, B, C \in K(H)$ such that $\begin{bmatrix} A & B \\ B^* & C \end{bmatrix} \geq 0$, then

$$(2.1) \quad 2s_j(B) \leq s_j \begin{bmatrix} A & B \\ B^* & C \end{bmatrix},$$

for $j = 1, 2, \dots$

Here, we give another proof for above inequality.

Let $\begin{bmatrix} A & B \\ B^* & C \end{bmatrix} \geq 0$ then $\begin{bmatrix} A & -B \\ -B^* & C \end{bmatrix} \geq 0$ and have the same singular values (see[1, Theorem 2.1]). So, we can write

$$\begin{bmatrix} 0 & 2B \\ 2B^* & 0 \end{bmatrix} \leq \begin{bmatrix} A & B \\ B^* & C \end{bmatrix},$$

and

$$\begin{bmatrix} 0 & -2B \\ -2B^* & 0 \end{bmatrix} \leq \begin{bmatrix} A & -B \\ -B^* & C \end{bmatrix}.$$

On the other hand, we know that for every self-adjoint compact operator X we have $s_j(X) \leq \lambda_j(X \oplus -X)$, for all $j = 1, 2, \dots$. By using of this fact we obtain

$$\begin{aligned} s_j \left(\begin{bmatrix} 0 & 2B \\ 2B^* & 0 \end{bmatrix} \right) &= \lambda_j \left(\begin{bmatrix} 0 & 2B \\ 2B^* & 0 \end{bmatrix} \oplus \begin{bmatrix} 0 & -2B \\ -2B^* & 0 \end{bmatrix} \right) \\ &\leq \lambda_j \left(\begin{bmatrix} A & B \\ B^* & C \end{bmatrix} \oplus \begin{bmatrix} A & -B \\ -B^* & C \end{bmatrix} \right) \\ &= s_j \left(\begin{bmatrix} A & B \\ B^* & C \end{bmatrix} \oplus \begin{bmatrix} A & -B \\ -B^* & C \end{bmatrix} \right). \end{aligned}$$

So, we obtain

$$s_j \left(\begin{bmatrix} 0 & 2B \\ 2B^* & 0 \end{bmatrix} \right) \leq s_j \left(\begin{bmatrix} A & B \\ B^* & C \end{bmatrix} \oplus \begin{bmatrix} A & -B \\ -B^* & C \end{bmatrix} \right).$$

Equivalently,

$$2s_j(B \oplus B^*) \leq \left(\left[\begin{array}{cc} A & B \\ B^* & C \end{array} \right] \oplus \left[\begin{array}{cc} A & -B \\ -B^* & C \end{array} \right] \right).$$

Since $s_j(B) = s_j(B^*)$ and $s_j \left(\left[\begin{array}{cc} A & B \\ B^* & C \end{array} \right] \right) = s_j \left(\left[\begin{array}{cc} A & -B \\ -B^* & C \end{array} \right] \right)$, we have

$$2s_j(B) \leq s_j \left(\left[\begin{array}{cc} A & B \\ B^* & C \end{array} \right] \right).$$

In [1, Remark 2.2], Audeh and Kittaneh proved that for every $A, B, C \in K(H)$ such that $\left[\begin{array}{cc} A & B \\ B^* & C \end{array} \right] \geq 0$, then

$$(2.2) \quad s_j \left(\left[\begin{array}{cc} A & B \\ B^* & C \end{array} \right] \right) \leq 2s_j(A \oplus C),$$

for $j = 1, 2, \dots$. Therefore, by inequality (2.1) we have the following inequality

$$(2.3) \quad s_j(B) \leq s_j(A \oplus C),$$

for $j = 1, 2, \dots$. Since every unitarily invariant norm is a monotone function of the singular values of an operator, we can write

$$(2.4) \quad \left\| \left\| \left[\begin{array}{cc} A & B \\ B^* & C \end{array} \right] \right\| \right\| \leq 2 \left\| \|A \oplus C\| \right\|.$$

We can obtain the reverse of inequality (2.4) for arbitrary operators $X, Y \in B(H)$ by pointing out the following inequality holds because of norm property

$$\| \|X + Y\| \| \leq \| \|X\| \| + \| \|Y\| \|.$$

Replace X and Y by $X - Y$ and $X + Y$, respectively. We have

$$2 \| \|X\| \| \leq \| \|X - Y\| \| + \| \|X + Y\| \|,$$

for all $X, Y \in B(H)$.

Let $X = \begin{bmatrix} A & 0 \\ 0 & C \end{bmatrix}$ and $Y = \begin{bmatrix} 0 & B \\ B^* & 0 \end{bmatrix}$ in above inequality. So,

$$\begin{aligned} 2 \left\| \left\| \begin{bmatrix} A & 0 \\ 0 & C \end{bmatrix} \right\| \right\| &\leq \left\| \left\| \begin{bmatrix} A & B \\ B^* & C \end{bmatrix} \right\| \right\| + \left\| \left\| \begin{bmatrix} A & -B \\ -B^* & C \end{bmatrix} \right\| \right\| \\ &= 2 \left\| \left\| \begin{bmatrix} A & B \\ B^* & C \end{bmatrix} \right\| \right\|. \end{aligned}$$

Hence,

$$\| \|A \oplus C\| \| \leq \left\| \left\| \begin{bmatrix} A & B \\ B^* & C \end{bmatrix} \right\| \right\|,$$

for all $A, B, C \in B(H)$. $\begin{bmatrix} A & 0 \\ 0 & C \end{bmatrix}$ is called a *pinching* of $\begin{bmatrix} A & B \\ B^* & C \end{bmatrix}$.

For operator norm we have

$$\max\{\|A\|, \|C\|\} \leq \left\| \left\| \begin{bmatrix} A & B \\ B^* & C \end{bmatrix} \right\| \right\|.$$

Here we give a generalization of the inequality which has been proved by Bhatia and Kittaneh in [5]. They have shown that if A and B are two $n \times n$ matrices, then

$$s_j(A + B) \leq s_j((|A| + |B|) \oplus (|A^*| + |B^*|)),$$

for $1 \leq j \leq n$.

For giving a generalization of above inequality, we need the following lemmas.

In the rest of this section, we always assume that f and g are non-negative functions on $[0, \infty)$ which are continuous and satisfying the relation $f(t)g(t) = t$ for all $t \in [0, \infty)$.

The following lemma is due to Kittaneh [7].

Lemma 2.1. *Let A, B , and C be operators in $B(H)$ such that A and B are positive and $BC = CA$. If $\begin{bmatrix} A & C^* \\ C & B \end{bmatrix}$ is positive in $B(H \oplus H)$, then $\begin{bmatrix} f(A)^2 & C^* \\ C & g(B)^2 \end{bmatrix}$ is also positive.*

Let T be an operator in $B(H)$. We know that $\begin{bmatrix} |T| & T^* \\ T & |T^*| \end{bmatrix} \geq 0$, if T is normal then we have $\begin{bmatrix} |T| & T^* \\ T & |T| \end{bmatrix} \geq 0$, (see [4]).

Lemma 2.2. *Let A be an operator in $B(H)$. Then we have*

$$(2.5) \quad \begin{bmatrix} |A|^{2\alpha} & A^* \\ A & |A^*|^{2(1-\alpha)} \end{bmatrix} \geq 0,$$

where $0 \leq \alpha \leq 1$.

Proof. It is easy to check that $A|A|^2 = |A^*|^2A$, then we have $A|A| = |A^*|A$ for $A \in B(H)$. Now by making use of Lemma 2.1, for $f(t) = t^\alpha$ and $g(t) = t^{1-\alpha}$, $0 \leq \alpha \leq 1$, and positivity of $\begin{bmatrix} |A| & A^* \\ A & |A^*| \end{bmatrix}$, we obtain the result. \square

Theorem 2.3. *Let A and B be two operators in $K(H)$. Then we have*

$$s_j(A + B) \leq s_j((|A|^{2\alpha} + |B|^{2\alpha}) \oplus (|A^*|^{2(1-\alpha)} + |B^*|^{2(1-\alpha)})),$$

for $j = 1, 2, \dots$ where $0 \leq \alpha \leq 1$.

Proof. Since sum of two positive operator is positive, Lemma 2.2 implies that

$$\begin{bmatrix} |A|^{2\alpha} + |B|^{2\alpha} & A^* + B^* \\ A + B & |A^*|^{2(1-\alpha)} + |B^*|^{2(1-\alpha)} \end{bmatrix} \geq 0,$$

By inequality (2.3) we have the result. \square

Corollary 2.4. *Let A and B be two operators in $K(H)$. Then we have*

$$s_j(A + B) \leq s_j((|A| + |B|) \oplus (|A^*| + |B^*|)),$$

for $j = 1, 2, \dots$

Proof. Let $\alpha = \frac{1}{2}$ in Theorem 2.3. □

It is easy to see that if A and B are normal operator in $K(H)$, then we have

$$s_j(A + B) \leq s_j((|A| + |B|) \oplus (|A| + |B|)),$$

for $j = 1, 2, \dots$

On the other hand, for $\alpha = 1$ in Theorem 2.3, we have

$$\begin{aligned} s_j(A + B) &\leq s_j(|A|^2 + |B|^2 \oplus 2I) \\ &= s_j(|A|^2 + |B|^2) \cup s_j(2I) \\ &= s_j(A^*A + B^*B) \cup s_j(2I), \end{aligned}$$

for $j = 1, 2, \dots$

Theorem 2.5. *Let A, B and X be operators in $B(H)$ such that X is compact. Then we have the following*

$$s_j(AXB^*) \leq s_j(A^*f(|X|)^2A \oplus B^*g(|X^*|)^2B),$$

for $j = 1, 2, \dots$

Proof. Since $\begin{bmatrix} |X| & X^* \\ X & |X^*| \end{bmatrix} \geq 0$, by Lemma 2.1 we have

$$Y = \begin{bmatrix} f(|X|)^2 & X^* \\ X & g(|X^*|)^2 \end{bmatrix} \geq 0.$$

Let $Z = \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}$. Since Y is positive, we have

$$Z^*YZ = \begin{bmatrix} A^*f(|X|)^2A & A^*X^*B \\ B^*XA & B^*g(|X^*|)^2B \end{bmatrix} \geq 0.$$

Hence, by inequality (2.3), we have the desired result. □

In above theorem, let X be a normal operator. Then we have

$$s_j(AXB^*) \leq s_j(A^*f(|X|)^2A \oplus B^*g(|X|)^2B),$$

for $j = 1, 2, \dots$

Corollary 2.6. *Let A, B and X be operators in $B(H)$ such that X is compact. Then we have*

$$s_j(AXB^*) \leq s_j(A^*|X|A \oplus B^*|X^*|B),$$

for $j = 1, 2, \dots$

Proof. Let $f(t) = t^{\frac{1}{2}}$ and $g(t) = t^{\frac{1}{2}}$ in Theorem 2.5. □

Here, we apply above corollary to show that singular values of AXB^* are dominated by singular values of $\|X\|(A \oplus B)$. For our proof we need the following lemma.

Lemma 2.7. [2, p. 75] *Let $A, B \in B(H)$ such that B is compact. Then*

$$s_j(AB) \leq \|A\|s_j(B),$$

for $j = 1, 2, \dots$

Theorem 2.8. *Let $A, B, X \in B(H)$ such that A and B are arbitrary compact. Then, we have*

$$s_j(AXB^*) \leq \|X\|s_j^2(A \oplus B),$$

for $j = 1, 2, \dots$

Proof. From Corollary 2.6 we have

$$\begin{aligned}
s_j(AXB^*) &\leq s_j(A^*|X|A \oplus B^*|X^*|B) \\
&= s_j\left(\begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}^* \begin{bmatrix} |X| & 0 \\ 0 & |X^*| \end{bmatrix} \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}\right) \\
&= s_j\left(\begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}^* \begin{bmatrix} |X|^{\frac{1}{2}} & 0 \\ 0 & |X^*|^{\frac{1}{2}} \end{bmatrix}^* \begin{bmatrix} |X|^{\frac{1}{2}} & 0 \\ 0 & |X^*|^{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}\right) \\
&= s_j\left(\left(\begin{bmatrix} |X|^{\frac{1}{2}} & 0 \\ 0 & |X^*|^{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}\right)^* \left(\begin{bmatrix} |X|^{\frac{1}{2}} & 0 \\ 0 & |X^*|^{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}\right)\right) \\
&= s_j\left(\left\|\begin{bmatrix} |X|^{\frac{1}{2}} & 0 \\ 0 & |X^*|^{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}\right\|^2\right) \\
&= s_j^2\left(\begin{bmatrix} |X|^{\frac{1}{2}} & 0 \\ 0 & |X^*|^{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}\right) \\
&\leq \left\|\begin{bmatrix} |X|^{\frac{1}{2}} & 0 \\ 0 & |X^*|^{\frac{1}{2}} \end{bmatrix}\right\|^2 s_j^2(A \oplus B) \\
&= \|X\| s_j^2(A \oplus B),
\end{aligned}$$

for $j = 1, 2, \dots$. The last inequality follows by Lemma 2.7. \square

In Theorem 2.8, let A and B be positive operators in $K(H)$. Then we have

$$(2.6) \quad s_j(A^{\frac{1}{2}}XB^{\frac{1}{2}}) \leq \|X\|s_j(A \oplus B),$$

for $j = 1, 2, \dots$

Corollary 2.9. *Let A and B be two operators in $K(H)$. Then we have*

$$(2.7) \quad s_j(AB^*) \leq s_j(A^*A \oplus B^*B),$$

for $j = 1, 2, \dots$

Proof. Let $X = I$ in Corollary 2.6. \square

Moreover, we can write inequality (2.7) in the following form

$$\begin{aligned} s_j(AB^*) &\leq s_j(|A|^2 \oplus |B|^2) \\ &= s_j^2(|A| \oplus |B|) = s_j^2(A \oplus B), \end{aligned}$$

for $j = 1, 2, \dots$

We should note here that inequality (2.7) can be obtained by Theorem 1 in [3] and Corollary 2.2 in [6].

Here, we give two results of Corollary 2.9. As the first application, let $A = \begin{bmatrix} X & Y \\ 0 & 0 \end{bmatrix}$ and $B = \begin{bmatrix} Y & -X \\ 0 & 0 \end{bmatrix}$, such that $X, Y \in K(H)$ then by easy computations we have

$$s_j(XY^* - YX^*) \leq s_j((XX^* + YY^*) \oplus (XX^* + YY^*)),$$

for $j = 1, 2, \dots$

For obtaining second application, replace A and B in (2.7) by AX^α and $BX^{(1-\alpha)}$ respectively, where X is a compact positive operator and $\alpha \in \mathbb{R}$. So, we have

$$\begin{aligned} s_j(AXB^*) &\leq s_j(X^\alpha A^* AX^\alpha \oplus X^{(1-\alpha)} B^* BX^{(1-\alpha)}) \\ &= s_j \left(\begin{bmatrix} X^\alpha A^* AX^\alpha & 0 \\ 0 & X^{(1-\alpha)} B^* BX^{(1-\alpha)} \end{bmatrix} \right) \\ &= s_j \left(\begin{bmatrix} X^\alpha A^* & 0 \\ 0 & X^{(1-\alpha)} B^* \end{bmatrix} \begin{bmatrix} AX^\alpha & 0 \\ 0 & BX^{(1-\alpha)} \end{bmatrix} \right) \\ &= s_j \left(\begin{bmatrix} AX^\alpha & 0 \\ 0 & BX^{(1-\alpha)} \end{bmatrix} \begin{bmatrix} X^\alpha A^* & 0 \\ 0 & X^{(1-\alpha)} B^* \end{bmatrix} \right) \\ &= s_j \left(\begin{bmatrix} AX^{2\alpha} A^* & 0 \\ 0 & BX^{2(1-\alpha)} B^* \end{bmatrix} \right) \\ &= s_j(AX^{2\alpha} A^* \oplus BX^{2(1-\alpha)} B^*), \end{aligned}$$

for all $j = 1, 2, \dots$

Finally, we have

$$(2.8) \quad s_j(AXB^*) \leq s_j(AX^{2\alpha} A^* \oplus BX^{2(1-\alpha)} B^*),$$

for all $j = 1, 2, \dots$

By a similar proof of Theorem 2.8 to inequality (2.8), we obtain

$$s_j(AXB^*) \leq \max\{\|X^{2\alpha}\|, \|X^{2(1-\alpha)}\|\} s_j^2(A \oplus B),$$

for all $j = 1, 2, \dots$

In above inequality, for positive operators A and B in $K(H)$ we have

$$s_j(A^{\frac{1}{2}}XB^{\frac{1}{2}}) \leq \max\{\|X^{2\alpha}\|, \|X^{2(1-\alpha)}\|\} s_j(A \oplus B)$$

for all $j = 1, 2, \dots$

3. Some singular value inequalities for normal operators

Here we give some results for compact normal operators. For every operator A , the Cartesian decomposition is to write $A = \Re(A) + i\Im(A)$, where $\Re(A) = \frac{A+A^*}{2}$ and $\Im(A) = \frac{A-A^*}{2i}$. If A is normal operator then $\Re(A)$ and $\Im(A)$ commute together and vice versa.

Theorem 3.1. *Let A_1, A_2, \dots, A_n be normal operators in $K(H)$. Then we have*

$$\begin{aligned} \frac{1}{\sqrt{2}} s_j(\oplus_{i=1}^n (\Re(A_i) + \Im(A_i))) &\leq s_j(\oplus_{i=1}^n A_i) \\ &\leq s_j(\oplus_{i=1}^n (|\Re(A_i)| + |\Im(A_i)|)), \end{aligned}$$

for $j = 1, 2, \dots$

Proof. Let A_1, A_2, \dots, A_n be normal operators, then

$$\oplus_{i=1}^n A_i = \begin{pmatrix} A_1 & & 0 \\ & A_2 & \\ & & \ddots \\ 0 & & & A_n \end{pmatrix}$$

is normal, so we have

$$(\oplus_{i=1}^n \Re(A_i))(\oplus_{i=1}^n \Im(A_i)) = (\oplus_{i=1}^n \Im(A_i))(\oplus_{i=1}^n \Re(A_i)).$$

By above equation, we obtain the following

$$\sqrt{(\oplus_{i=1}^n A_i)^*(\oplus_{i=1}^n A_i)} = \sqrt{(\oplus_{i=1}^n \Re(A_i))^2 + (\oplus_{i=1}^n \Im(A_i))^2}.$$

So

$$\begin{aligned}
s_j(\oplus_{i=1}^n A_i) &= s_j(|\oplus_{i=1}^n A_i|) \\
&= s_j\left(\sqrt{(\oplus_{i=1}^n A_i)^*(\oplus_{i=1}^n A_i)}\right) \\
&= s_j\left(\sqrt{(\oplus_{i=1}^n \Re(A_i))^2 + (\oplus_{i=1}^n \Im(A_i))^2}\right),
\end{aligned}$$

for $j = 1, 2, \dots$

By using Weyl's monotonicity principle [2] and the inequality

$$\sqrt{(\oplus_{i=1}^n \Re(A_i))^2 + (\oplus_{i=1}^n \Im(A_i))^2} \leq |\oplus_{i=1}^n \Re(A_i)| + |\oplus_{i=1}^n \Im(A_i)|,$$

we have the following

$$s_j\left(\sqrt{(\oplus_{i=1}^n \Re(A_i))^2 + (\oplus_{i=1}^n \Im(A_i))^2}\right) \leq s_j(|\oplus_{i=1}^n \Re(A_i)| + |\oplus_{i=1}^n \Im(A_i)|),$$

for $j = 1, 2, \dots$. Now for proving left side inequality, we recall the following inequality

$$0 \leq (\Re(A_i) + \Im(A_i))^*(\Re(A_i) + \Im(A_i)) \leq 2(\Re(A_i)^2 + \Im(A_i)^2).$$

Therefore, by using the Weyl's monotonicity principle we can write

$$s_j\left(\sqrt{((\oplus_{i=1}^n \Re(A_i)) + (\oplus_{i=1}^n \Im(A_i)))^*((\oplus_{i=1}^n \Re(A_i)) + (\oplus_{i=1}^n \Im(A_i)))}\right),$$

which is less than

$$\sqrt{2}s_j\left(\sqrt{(\oplus_{i=1}^n \Re(A_i))^2 + (\oplus_{i=1}^n \Im(A_i))^2}\right).$$

for $j = 1, 2, \dots$. Therefore,

$$\begin{aligned}
s_j((\oplus_{i=1}^n \Re(A_i)) + (\oplus_{i=1}^n \Im(A_i))) &= s_j(|(\oplus_{i=1}^n \Re(A_i)) + (\oplus_{i=1}^n \Im(A_i))|) \\
&\leq \sqrt{2}s_j(\sqrt{(\oplus_{i=1}^n \Re(A_i))^2 + (\oplus_{i=1}^n \Im(A_i))^2}).
\end{aligned}$$

for $j = 1, 2, \dots$ □

The following example shows that normal condition is necessary.

Example 3.2. Let $A = \begin{bmatrix} -1+i & 1 \\ i & 1+2i \end{bmatrix}$, then a calculation shows

$$s_2(\Re(A) + i\Im(A)) \approx 1.34 > s_2(|\Re(A)| + |\Im(A)|) \approx 1.27.$$

Corollary 3.3. *Let A be a normal operator in $K(H)$. Then we have*

$$(1/\sqrt{2})s_j(\Re(A) + \Im(A)) \leq s_j(A) \leq s_j(|\Re(A)| + |\Im(A)|),$$

for $j = 1, 2, \dots$

For each complex number $x = a+ib$, we know the following inequality holds

$$(3.1) \quad \frac{1}{\sqrt{2}}|a + b| \leq |x| \leq |a| + |b|.$$

Now, by applying Corollary 3.3, we can obtain operator version of inequality (3.1).

Here, we determine the upper and lower bound for $A + iA^*$.

Theorem 3.4. *Let A_1, A_2, \dots, A_n be in $K(H)$. Then*

$$\begin{aligned} \sqrt{2}s_j(\oplus_{i=1}^n(\Re(A_i) + \Im(A_i))) &\leq s_j(\oplus_{i=1}^n(A_i + iA_i^*)) \\ &\leq 2s_j(\oplus_{i=1}^n(\Re(A_i) + \Im(A_i))), \end{aligned}$$

for $j = 1, 2, \dots$

Proof. Note that $A_i + iA_i^*$ is normal operator for $i = 1, \dots, n$, so $T = \oplus_{i=1}^n(A_i + iA_i^*)$ is normal. On the other hand, we can write $T = \Re(T) + i\Im(T)$ where

$$\Re(T) = (\oplus_{i=1}^n(A_i + A_i^*) + i \oplus_{i=1}^n(A_i^* - A_i))/2,$$

$$\Im(T) = (\oplus_{i=1}^n(A_i - A_i^*) + i \oplus_{i=1}^n(A_i^* + A_i))/2i.$$

It is enough to compare $\Re(T)$ and $\Im(T)$ to see $\Re(T) = \Im(T)$. So

$$(3.2) \quad \Re(T) + \Im(T) = \oplus_{i=1}^n(A_i + A_i^*) + i \oplus_{i=1}^n(A_i^* - A_i).$$

Now apply Theorem 3.1, we have

$$(3.3) \quad \begin{aligned} (1/\sqrt{2})s_j(\Re(T) + \Im(T)) &\leq s_j(\Re(T) + i\Im(T)) \\ &\leq s_j(|\Re(T)| + |\Im(T)|), \end{aligned}$$

for $j = 1, 2, \dots$. Put (3.2), $\Re(T) + i\Im(T) = \oplus_{i=1}^n(A_i + iA_i^*)$ and $\Re(T)$ in (3.3) to obtain

$$(3.4) \quad (1/\sqrt{2})s_j(\oplus_{i=1}^n(A_i + A_i^*) + i \oplus_{i=1}^n(A_i^* - A_i)) \leq s_j(\oplus_{i=1}^n(A_i + iA_i^*)),$$

and

$$\begin{aligned} s_j(\oplus_{i=1}^n (A_i + iA_i^*)) &\leq 2s_j(\oplus_{i=1}^n (A_i + A_i^*)/2 + i \oplus_{i=1}^n (A_i^* - A_i)/2) \\ &= s_j(\oplus_{i=1}^n (A_i + A_i^*) + i \oplus_{i=1}^n (A_i^* - A_i)), \end{aligned}$$

for $j = 1, 2, \dots$. By writing $\Re(\oplus_{i=1}^n A_i) = \oplus_{i=1}^n (A_i + A_i^*)/2$ and $\Im(\oplus_{i=1}^n A_i) = \oplus_{i=1}^n (A_i - A_i^*)/2i$ we have

$$\begin{aligned} (1/\sqrt{2})s_j(2\Re(\oplus_{i=1}^n A_i) + 2\Im(\oplus_{i=1}^n A_i)) &\leq s_j(\oplus_{i=1}^n (A_i + iA_i^*)) \\ &\leq s_j(2\Re(\oplus_{i=1}^n A_i) + 2\Im(\oplus_{i=1}^n A_i)), \end{aligned}$$

for $j = 1, 2, \dots$. Finally

$$\begin{aligned} \sqrt{2}s_j(\oplus_{i=1}^n (\Re(A_i) + \Im(A_i))) &\leq s_j(\oplus_{i=1}^n (A_i + iA_i^*)) \\ &\leq 2s_j(\oplus_{i=1}^n (\Re(A_i) + \Im(A_i))), \end{aligned}$$

for $j = 1, 2, \dots$ □

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