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Title	Norms of some singular integral operators and their inverse operators
Author(s)	Nakazi, T.; Yamamoto, T.
Citation	Hokkaido University Preprint Series in Mathematics, 387, 1-28
Issue Date	1997-09-01
DOI	https://doi.org/10.14943/83533
Doc URL	https://hdl.handle.net/2115/69137
Type	departmental bulletin paper
File Information	re387.pdf



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AND THEIR INVERSE OPERATORS**

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Series #387. September 1997

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NORMS OF SOME SINGULAR INTEGRAL OPERATORS AND THEIR INVERSE OPERATORS

by

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Abstract. Let α and β be bounded measurable functions on the unit circle T . Then the singular integral operator $S_{\alpha,\beta}$ is defined by $S_{\alpha,\beta}f = \alpha P_+f + \beta P_-f$, ($f \in L^2(T)$) where P_+ is an analytic projection and P_- is a co-analytic projection. In this paper, the norms of $S_{\alpha,\beta}$ and its inverse operator on the Hilbert space $L^2(T)$ are calculated in general, using α, β and $\alpha\bar{\beta} + H^\infty$. Moreover, the relations between these and the norms of Hankel operators are established. As an application, in some special case in which α and β are nonconstant functions, the norm of $S_{\alpha,\beta}$ is calculated in a completely explicit form. If α and β are constant functions, then it is well known that the norm of $S_{\alpha,\beta}$ on $L^2(T)$ is equal to $\max\{|\alpha|, |\beta|\}$. If α and β are nonzero constant functions, then it is also known that $S_{\alpha,\beta}$ on $L^2(T)$ has an inverse operator $S_{\alpha^{-1},\beta^{-1}}$ whose norm is equal to $\max\{|\alpha|^{-1}, |\beta|^{-1}\}$.

Keywords: Singular integral operators, Hardy spaces, Hankel operators, Toeplitz operators.

AMS Subject Classification: Primary 45E10, 47B35; Secondary 46J15.

1. INTRODUCTION

Let m denote the normalized Lebesgue measure on the unit circle $T = \{\zeta; |\zeta| = 1\}$. That is, $dm(\zeta) = d\theta/2\pi$ for $\zeta = e^{i\theta}$. The inner product in the Hilbert space $L^2 = L^2(T)$ is given by

$$(f, g) = \int_T f(\zeta) \overline{g(\zeta)} dm(\zeta).$$

The norm in L^2 is given by $\|f\|_2 = \sqrt{(f, f)}$. By $L^\infty = L^\infty(T)$ we denote the space of essentially bounded Lebesgue measurable functions. The norm in L^∞ is given by $\|f\|_\infty = \text{ess sup}_T |f|$. Let H^2 (resp. H^∞) be the Hardy space of functions $f \in L^2$ (resp. $f \in L^\infty$) whose negative Fourier coefficients are zero. Let $\overline{H}_0^2$ be the space of functions $f \in L^2$ whose nonnegative Fourier coefficients are zero. Then $L^2 = H^2 \oplus \overline{H}_0^2$. Let S be the singular integral operator defined by

$$(Sf)(\zeta) = \frac{1}{\pi i} \int_T \frac{f(\eta)}{\eta - \zeta} d\eta \quad (a.e. \zeta \in T),$$

where the integral is understood in the sense of Cauchy's principal value (cf. [4, p.12]). If f is in L^1 , then $Sf(\zeta)$ exists for almost everywhere ζ on T , and Sf becomes a Lebesgue measurable function on T . Let an analytic projection and a co-analytic projection be

$$P_+ = (I + S)/2, \quad \text{and} \quad P_- = (I - S)/2,$$

where I denotes the identity operator. If $\alpha, \beta \in L^\infty$, then the singular integral operator $S_{\alpha, \beta}$ on L^2 is defined by

$$S_{\alpha, \beta} f = \alpha P_+ f + \beta P_- f, \quad (f \in L^2).$$

Then $S_{1,1} = I$, $S_{1,-1} = S$, $S_{1,0} = P_+$ and $S_{0,1} = P_-$. The norm of $S_{\alpha, \beta}$ is defined by

$$\|S_{\alpha, \beta}\| = \sup_{f \in L^2, \|f\|_2=1} \|S_{\alpha, \beta} f\|_2.$$

Since $\|P_+\| = \|P_-\| = 1$, we have

$$\|S_{\alpha, \beta}\| \leq \|\alpha\|_\infty + \|\beta\|_\infty < \infty.$$

Hence, $S_{\alpha,\beta}$ is a bounded operator on L^2 . Furthermore, it is well known that

$$\max \{ \|\alpha\|_\infty, \|\beta\|_\infty \} \leq \|S_{\alpha,\beta}\| \leq \left\| \sqrt{|\alpha|^2 + |\beta|^2} \right\|_\infty.$$

If α and β are constant functions, then it is well known and not difficult to establish that

$$\|S_{\alpha,\beta}\| = \max \{ |\alpha|, |\beta| \}$$

(cf. [3]). If α and β are nonconstant functions, then we will show in Section 2 that the formula of $\|S_{\alpha,\beta}\|$ is more complicated.

If $\phi \in L^\infty$, then the Toeplitz operator T_ϕ is defined by $T_\phi f = P_+(\phi f)$ for $f \in H^2$. This operator is bounded, and its norm is equal to $\|\phi\|_\infty$ (cf. [2, p.179]). The Hankel operator H_ϕ is defined by $H_\phi f = P_-(\phi f)$ for $f \in H^2$. This operator is bounded, and by the Nehari theorem [8] (cf. [9, p.181]), its norm is equal to $\inf \{ \|\phi - k\|_\infty; k \in H^\infty \}$. Hence,

$$\|H_\phi\| \leq \|T_\phi\| \leq \|S_{\phi,1}\|.$$

Though the norm of T_ϕ or H_ϕ is known, the norm of $S_{\phi,1}$ is not known.

In this paper, we consider the operator $S_{\alpha,\beta}$ on L^2 for functions $\alpha, \beta \in L^\infty$. In Section 2, we give the formula of the norm of $S_{\alpha,\beta}$ on L^2 for $\alpha, \beta \in L^\infty$, which involve lower bounds over the algebra H^∞ . It is a little surprising that the norm of the singular integral operator $S_{\alpha,\beta}$ is related to the norm of the Hankel operator $H_{\alpha\bar{\beta}}$ for some special α and β . In Section 3, we also give the formula of the norm of $S_{\alpha,\beta}^{-1}$ on L^2 for $\alpha, \beta \in L^\infty$, which involve upper bounds over the algebra H^∞ . If $S_{\alpha,\beta}$ is invertible, then $\text{ess inf}_T (\min \{ |\alpha|, |\beta| \}) > 0$. When $\phi = \alpha/\beta$ and $\text{ess inf}_T (\min \{ |\alpha|, |\beta| \}) > 0$,

$$S_{\alpha,\beta} = \beta S_{\phi,1} = \beta(P_+\phi P_+ + P_-)(I + P_-\phi P_+).$$

Then $I + P_-\phi P_+$ is invertible and $(I + P_-\phi P_+)^{-1} = I - P_-\phi P_+$ (cf. [9, p.393]). Hence, $S_{\alpha,\beta}$ is invertible if and only if $\min \{ \text{ess inf}_T |\alpha|, \text{ess inf}_T |\beta| \} > 0$ and $T_{\alpha/\beta}$ is invertible.

The first author (cf. [7]) calculated essentially the norm of the operator inverse to T_ϕ . We will show in Section 3 that the formula of the norm of the operator inverse to T_ϕ is similar to the formula of the norm of the operator inverse to $S_{\alpha,\beta}$. The second author (cf. [11]) considered the norm of $S_{\alpha,\beta}$ on the weighted space $L^2(T, W)$ with a weight function W on T , and proved the Feldman-Krupnik-Markus theorem [3] using the Cotlar-Sadosky lifting theorem [1] when α and β are constant functions.

2. NORM OF THE OPERATOR $S_{\alpha,\beta}$

If $\alpha, \beta \in L^\infty$, then the following inequality is well known and not difficult to establish.

$$\max \{ \|\alpha\|_\infty, \|\beta\|_\infty \} \leq \|S_{\alpha,\beta}\| \leq \left\| \sqrt{|\alpha|^2 + |\beta|^2} \right\|_\infty.$$

We should mention that

$$\max \{ \|\alpha\|_\infty, \|\beta\|_\infty \} = \left\| \frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{0 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} \right\|_\infty^{1/2},$$

and

$$\left\| \sqrt{|\alpha|^2 + |\beta|^2} \right\|_\infty = \left\| \frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{|\alpha\bar{\beta} - 0|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} \right\|_\infty^{1/2}.$$

It is not difficult to establish that

$$\|S_{\alpha,\beta}\|^2 \leq \left\| \frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} \right\|_\infty,$$

for any $k \in H^\infty$. The formula of the norm of $S_{\alpha,\beta}$ is as follows.

Theorem 1. Let $\alpha, \beta \in L^\infty$. Then

$$\|S_{\alpha,\beta}\|^2 = \inf_{k \in H^\infty} \left\| \frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} \right\|_\infty.$$

The infimum is attained.

Proof. For any $k \in H^\infty$, we define the quantity M_k according to

$$M_k = \left\| \frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} \right\|_\infty.$$

We prove that $\|S_{\alpha,\beta}\|^2 \geq \inf\{M_k; k \in H^\infty\}$. Let $\gamma = \|S_{\alpha,\beta}\|$. Then

$$\|S_{\alpha,\beta}f\|_2 \leq \gamma\|f\|_2, \quad (f \in L^2).$$

Let $W_1 = \gamma^2 - |\alpha|^2$, $W_2 = \gamma^2 - |\beta|^2$ and $W_3 = \gamma^2 - \alpha\bar{\beta}$. Then

$$(W_1 f_1, f_1) + (W_2 f_2, f_2) + 2\operatorname{Re}(W_3 f_1, f_2) \geq 0,$$

($f_1 \in H^2$, $f_2 \in \overline{H_0^2}$). By the Cotlar-Sadosky lifting theorem [1], $W_1 \geq 0$, $W_2 \geq 0$, and there exists a $g \in H^\infty$ such that

$$|W_3 - g|^2 \leq W_1 W_2.$$

Hence, $\gamma \geq \max\{|\alpha|, |\beta|\}$ and

$$|\gamma^2 - \alpha\bar{\beta} - g|^2 \leq (\gamma^2 - |\alpha|^2)(\gamma^2 - |\beta|^2).$$

Let $k_0 = \gamma^2 - g$. Then $k_0 \in H^\infty$ and $|\gamma^2 - \alpha\bar{\beta} - g| = |\alpha\bar{\beta} - k_0|$. Hence,

$$\begin{aligned} 0 &\leq (\gamma^2 - |\alpha|^2)(\gamma^2 - |\beta|^2) - |\alpha\bar{\beta} - k_0|^2 \\ &= \gamma^4 - (|\alpha|^2 + |\beta|^2)\gamma^2 + |\alpha\beta|^2 - |\alpha\bar{\beta} - k_0|^2. \end{aligned}$$

Suppose

$$\gamma^2 \leq \frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{|\alpha\bar{\beta} - k_0|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2}$$

on some measurable subset E of T . Since

$$\gamma^2 \geq \max\{|\alpha|^2, |\beta|^2\} = \frac{|\alpha|^2 + |\beta|^2}{2} + \left|\frac{|\alpha|^2 - |\beta|^2}{2}\right|$$

on T , we have

$$\left|\frac{|\alpha|^2 - |\beta|^2}{2}\right| + \sqrt{|\alpha\bar{\beta} - k_0|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2} \leq 0$$

on E . This implies $|\alpha| - |\beta| = |\alpha\bar{\beta} - k_0| = 0$ on E . Hence,

$$\gamma^2 \geq \max\{|\alpha|^2, |\beta|^2\} = \frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{|\alpha\bar{\beta} - k_0|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2}$$

on E . Therefore,

$$\gamma^2 \geq \frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{|\alpha\bar{\beta} - k_0|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2}$$

on T . Hence $M_{k_0} \leq \gamma^2$. Since $\gamma = \|S_{\alpha,\beta}\|$, we have

$$\inf_{k \in H^\infty} M_k \leq M_{k_0} \leq \|S_{\alpha,\beta}\|^2.$$

We prove that $\|S_{\alpha,\beta}\|^2 \leq \inf\{M_k; k \in H^\infty\}$. This is the easy direction of the theorem. For any $k \in H^\infty$, we have

$$(kf_1, f_2) = 0, \quad (f_1 \in H^2, f_2 \in \overline{H_0^2}).$$

Since

$$\frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2} \leq M_k,$$

we have

$$\begin{aligned} & (M_k - |\alpha|^2)(M_k - |\beta|^2) \\ & \geq \left(\sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2} - \frac{|\alpha|^2 - |\beta|^2}{2} \right) \\ & \quad \times \left(\sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2} + \frac{|\alpha|^2 - |\beta|^2}{2} \right) \\ & = |\alpha\bar{\beta} - k|^2. \end{aligned}$$

Hence,

$$\begin{aligned} & M_k \|f_1 + f_2\|_2^2 - \|\alpha f_1 + \beta f_2\|_2^2 \\ & = \left\| \sqrt{M_k - |\alpha|^2} f_1 \right\|_2^2 + \left\| \sqrt{M_k - |\beta|^2} f_2 \right\|_2^2 - 2\operatorname{Re}(\alpha\bar{\beta} f_1, f_2) \\ & \geq 2 \left\| \sqrt{M_k - |\alpha|^2} f_1 \right\|_2 \left\| \sqrt{M_k - |\beta|^2} f_2 \right\|_2 - 2\operatorname{Re}((\alpha\bar{\beta} - k) f_1, f_2) \\ & \geq 2 \int_T \left(\sqrt{M_k - |\alpha|^2} \sqrt{M_k - |\beta|^2} - |\alpha\bar{\beta} - k| \right) |f_1 f_2| dm \geq 0. \end{aligned}$$

Hence, for any $k \in H^\infty$,

$$\|S_{\alpha,\beta}f\|_2^2 \leq M_k \|f\|_2^2, \quad (f \in L^2).$$

Therefore,

$$\inf_{k \in H^\infty} M_k \leq M_{k_0} \leq \|S_{\alpha,\beta}\|^2 \leq \inf_{k \in H^\infty} M_k.$$

Hence the equalities hold, and the infimum is attained by $k = k_0$. This completes the proof.

Remark 1. Let $\alpha, \beta \in L^\infty$, let $\phi = \alpha\bar{\beta}$, and let $\psi = (|\alpha|^2 - |\beta|^2)/2$. Then

$$\|S_{\alpha,\beta}\|^2 = \inf_{k \in H^\infty} \left\| \sqrt{|\phi|^2 + \psi^2} + \sqrt{|\phi - k|^2 + \psi^2} \right\|_\infty.$$

The infimum is attained. If $|\alpha| = |\beta|$, then $\psi = 0$. Hence

$$\|S_{\alpha,\beta}\|^2 = \inf_{k \in H^\infty} \|\phi + \phi - k\|_\infty.$$

Corollary 1. If $|\alpha|$ and $|\beta|$ are constant functions, then

$$\|S_{\alpha,\beta}\|^2 = \frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{\|H_{\alpha\bar{\beta}}\|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2}.$$

Proof. It follows from Theorem 1 that

$$\begin{aligned} \|S_{\alpha,\beta}\|^2 &= \inf_{k \in H^\infty} \left\| \frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2} \right\|_\infty \\ &= \frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{\left(\inf_{k \in H^\infty} \|\alpha\bar{\beta} - k\|_\infty\right)^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2}. \end{aligned}$$

By the Nehari theorem [8], this proves the corollary.

Corollary 2. Let $\alpha, \beta \in L^\infty$. Then

$$\|S_{\alpha,\beta}\|^2 \leq \max\{\|\alpha\|_\infty^2, \|\beta\|_\infty^2\} + \|H_{\alpha\bar{\beta}}\|.$$

Proof. It follows from the easy direction of Theorem 1 that

$$\begin{aligned} \|S_{\alpha,\beta}\|^2 &\leq \inf_{k \in H^\infty} \left\| \frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2} \right\|_\infty \\ &\leq \inf_{k \in H^\infty} \left\| \frac{|\alpha|^2 + |\beta|^2}{2} + |\alpha\bar{\beta} - k| + \left| \frac{|\alpha|^2 - |\beta|^2}{2} \right| \right\|_\infty \\ &= \inf_{k \in H^\infty} \left\| \max\{|\alpha|^2, |\beta|^2\} + |\alpha\bar{\beta} - k| \right\|_\infty \\ &\leq \max\{\|\alpha\|_\infty^2, \|\beta\|_\infty^2\} + \inf_{k \in H^\infty} \|\alpha\bar{\beta} - k\|_\infty. \end{aligned}$$

By the Nehari theorem [8], this proves the corollary.

Remark 2. If $\alpha\bar{\beta} \in H^\infty$, then the infimum in Theorem 1 is attained by $k = \alpha\bar{\beta}$. In this case,

$$\|S_{\alpha,\beta}\| = \|\max\{|\alpha|, |\beta|\}\|_\infty = \max\{\|\alpha\|_\infty, \|\beta\|_\infty\}.$$

Hence the equality holds in Corollary 2 because $\|H_{\alpha\bar{\beta}}\| = 0$. By Corollary 1, if $|\alpha| = |\beta| = \text{constant}$, then the equality holds in Corollary 2.

By Corollary 2, if $\phi \in L^\infty$ and $\|\phi\|_\infty \leq 1$, then $\|S_{\phi,1}\|^2 \leq 1 + \|H_\phi\|$. By Corollary 1, if $|\phi| = 1$, then $\|S_{\phi,1}\|^2 = 1 + \|H_\phi\|$. When ϕ is a real function whose range consists of only two points, the norm of $S_{\phi,1}$ will be calculated in a completely explicit form in Corollary 3. For example, by Corollary 3, if E is a measurable subset of the unit circle T satisfying $0 < m(E) < 1$, then $\|S_{\chi_E,1}\| = 2/\sqrt{3}$. It is well known that $\|H_{\chi_E}\| = 1/2$. In this case, $\|S_{\chi_E,1}\|^2 < 1 + \|H_{\chi_E}\|$. Hence the equality does not hold in Corollary 2. We need Lemma 1 to prove Corollary 3.

Lemma 1. Let a and b be real numbers satisfying $a \neq b$. Then the equality

$$\frac{a^2 + 1}{2} + \sqrt{(a - x)^2 + \left(\frac{a^2 - 1}{2}\right)^2} = \frac{b^2 + 1}{2} + \sqrt{(b - x)^2 + \left(\frac{b^2 - 1}{2}\right)^2}$$

holds for some real number x if and only if $|a + b| < 2$. Then the x is unique and it is given by

$$x = x_0 = \frac{2(a + b)(1 - ab)}{4 - (a + b)^2}.$$

Proof. Suppose the equality holds for $x = 0$. Then $a^2 = b^2$. Since $a \neq b$, we have $a = -b$. Hence $|a + b| = 0 < 2$. Suppose the equality holds for some real number x satisfying $x \neq 0$. Then

$$\left\{ \frac{b^2 - a^2}{2} + \sqrt{(b - x)^2 + \left(\frac{b^2 - 1}{2}\right)^2} \right\}^2 = (a - x)^2 + \left(\frac{a^2 - 1}{2}\right)^2.$$

It follows by direct computation that

$$2(b^2 - a^2)\sqrt{(x - b)^2 + \left(\frac{b^2 - 1}{2}\right)^2} = (b - a) \{4x - (a + b)(b^2 + 1)\}.$$

Since $a \neq b$, we have

$$2(a + b)\sqrt{(x - b)^2 + \left(\frac{b^2 - 1}{2}\right)^2} = 4x - (a + b)(b^2 + 1).$$

Hence,

$$\{4 - (a + b)^2\}x^2 = 2(a + b)(1 - ab)x.$$

Since $x \neq 0$, we have

$$\{4 - (a + b)^2\}x = 2(a + b)(1 - ab).$$

If $(a + b)^2 = 4$, then $ab = 1$. Hence $a^2 = b^2 = 1$. Since $a \neq b$, we have $a + b = 0$. This contradiction implies $(a + b)^2 \neq 4$. Hence,

$$x = \frac{2(a + b)(1 - ab)}{4 - (a + b)^2}.$$

It follows by direct computation that

$$4x - (a+b)(b^2+1) = \frac{(a+b)\{(a-b)^2 + (b^2+ab-2)^2\}}{4-(a+b)^2}.$$

If $a \neq b$, then

$$2\sqrt{(x-b)^2 + \left(\frac{b^2-1}{2}\right)^2} = \frac{(a-b)^2 + (b^2+ab-2)^2}{4-(a+b)^2} > 0$$

because $(a-b)^2 > 0$. Hence, $|a+b| < 2$. This proof is reversible.

Corollary 3. Let E be a measurable subset of T satisfying $0 < m(E) < 1$, let a and b be real numbers, and let $\phi = a\chi_E + b\chi_{E^c}$. Then

(1) If $\max\{a^2, b^2\} \geq 2 - ab$, then

$$\|S_{\phi,1}\| = \max\{|a|, |b|\}.$$

(2) If $\max\{a^2, b^2\} < 2 - ab$, then

$$\|S_{\phi,1}\|^2 = \frac{4(1-ab)}{4-(a+b)^2}.$$

Proof. We define the functions $f(x)$ and $g(x)$ according to

$$f(x) = \frac{a^2+1}{2} + \sqrt{(a-x)^2 + \left(\frac{a^2-1}{2}\right)^2},$$

and

$$g(x) = \frac{b^2+1}{2} + \sqrt{(b-x)^2 + \left(\frac{b^2-1}{2}\right)^2}.$$

For the real number x_0 defined in Lemma 1, it follows that

$$\begin{aligned} f(x_0) &= g(x_0) \\ &= \frac{a^2+1}{2} + \sqrt{\left(\frac{(a-b)(a^2+ab-2)}{4-(a+b)^2}\right)^2 + \left(\frac{a^2-1}{2}\right)^2} \end{aligned}$$

$$\begin{aligned}
&= \frac{b^2 + 1}{2} + \sqrt{\left(\frac{(a-b)(b^2 + ab - 2)}{4 - (a+b)^2}\right)^2 + \left(\frac{b^2 - 1}{2}\right)^2} \\
&= \frac{4(1 - ab)}{4 - (a+b)^2}.
\end{aligned}$$

We prove (1). Since $\max\{a^2, b^2\} \geq ab$ and $\max\{a^2, b^2\} \geq 2 - ab$, we have $\max\{a^2, b^2\} \geq 1$. Hence, $\max\{a^2, b^2, 1\} = \max\{a^2, b^2\}$. Since $\|\phi\|_\infty = \max\{|a|, |b|\}$ and $\max\{\|\phi\|_\infty, 1\} \leq \|S_{\phi,1}\|$, we have

$$\max\{a^2, b^2\} = \max\{a^2, b^2, 1\} \leq \|S_{\phi,1}\|^2.$$

Suppose $a = b$. Then ϕ becomes a constant function. Hence, by Remark 2,

$$\|S_{\phi,1}\| = \max\{|\phi|, 1\} = \max\{|a|, |b|, 1\} = \max\{|a|, |b|\}.$$

Suppose $a \neq b$. Since $0 < m(E) < 1$, we have

$$\begin{aligned}
\|S_{\phi,1}\|^2 &\leq \inf_{x \in R} \left\| \frac{|\phi|^2 + 1}{2} + \sqrt{(\phi - x)^2 + \left(\frac{\phi^2 - 1}{2}\right)^2} \right\|_\infty \\
&= \inf_{x \in R} \|f(x)\chi_E + g(x)\chi_{E^c}\|_\infty = \inf_{x \in R} (\max\{f(x), g(x)\}).
\end{aligned}$$

By Lemma 1, if $|a + b| \geq 2$, then the equality $f(x) = g(x)$ does not hold for any real number x . Hence, $f(x) < g(x)$ or $f(x) > g(x)$. Hence,

$$\inf_{x \in R} (\max\{f(x), g(x)\}) = \max\{f(a), g(b)\}.$$

Since $f(a) = \max\{a^2, 1\}$ and $g(b) = \max\{b^2, 1\}$, we have

$$\max\{a^2, b^2\} \leq \|S_{\phi,1}\|^2 \leq \max\{f(a), g(b)\} = \max\{a^2, b^2, 1\} = \max\{a^2, b^2\}.$$

By Lemma 1, if $|a + b| < 2$, then the equation $f(x) = g(x)$ has a unique solution $x = x_0$ which is given in Lemma 1. Hence, $f(x_0) = g(x_0)$. Without loss of generality, we assume $a < b$. If $a \leq x_0 \leq b$, then $\max\{a^2, b^2\} \leq 2 - ab$. Since $\max\{a^2, b^2\} \geq 2 - ab$, we have $\max\{a^2, b^2\} = 2 - ab$. By this equality,

$$\max\{a^2, b^2\} \leq \|S_{\phi,1}\|^2 \leq \inf_{x \in R} (\max\{f(x), g(x)\})$$

$$= f(x_0) = g(x_0) = \frac{4(1-ab)}{4-(a+b)^2} = \max\{a^2, b^2\}.$$

If $x_0 \leq a \leq b$ or $a \leq b \leq x_0$, then

$$\begin{aligned} \max\{a^2, b^2\} &\leq \|S_{\phi,1}\|^2 \leq \inf_{x \in R} (\max\{f(x), g(x)\}) \\ &= \max\{f(a), g(b)\} = \max\{a^2, b^2, 1\} = \max\{a^2, b^2\}. \end{aligned}$$

We prove (2). Suppose $a = b$. Then ϕ becomes a constant function and $\phi = a = b$. Since $\max\{a^2, b^2\} < 2 - ab$, we have $a^2 = b^2 < 1$. By Remark 2,

$$\|S_{\phi,1}\|^2 = \max\{\phi^2, 1\} = \max\{a^2, 1\} = \max\{b^2, 1\} = 1.$$

Suppose $a \neq b$. It is sufficient to prove that $\|S_{\phi,1}\|^2 = f(x_0) = g(x_0)$. Without loss of generality, we assume $a < b$. Since $\max\{a^2, b^2\} < 2 - ab$, we have $a^2 + b^2 < 2(2 - ab)$. Hence $|a + b| < 2$. Let $f(x)$ and $g(x)$ be functions defined in the proof of (1). By Lemma 1, the equation $f(x) = g(x)$ has a unique solution $x = x_0$ which is given in Lemma 1. Hence, $f(x_0) = g(x_0)$. It follows by direct calculation that

$$a - x_0 = \frac{(b-a)(a^2 + ab - 2)}{4 - (a+b)^2} < 0,$$

$$b - x_0 = \frac{(a-b)(b^2 + ab - 2)}{4 - (a+b)^2} > 0.$$

Hence, $a < x_0 < b$. By Theorem 1, there exists a $k_0 \in H^\infty$ such that

$$\begin{aligned} \|S_{\phi,1}\|^2 &= \left\| \frac{|\phi|^2 + 1}{2} + \sqrt{|\phi - k_0|^2 + \left(\frac{|\phi|^2 - 1}{2}\right)^2} \right\|_\infty \\ &= \inf_{k \in H^\infty} \left\| \frac{|\phi|^2 + 1}{2} + \sqrt{|\phi - k|^2 + \left(\frac{|\phi|^2 - 1}{2}\right)^2} \right\|_\infty \\ &\leq \inf_{x \in R} \left\| \frac{|\phi|^2 + 1}{2} + \sqrt{|\phi - x|^2 + \left(\frac{|\phi|^2 - 1}{2}\right)^2} \right\|_\infty \end{aligned}$$

$$= \inf_{x \in R} \|f(x)\chi_E + g(x)\chi_{E^c}\|_\infty \leq \inf_{x \in R} (\max\{f(x), g(x)\}).$$

Since $a < x_0 < b$, we have

$$\inf_{x \in R} (\max\{f(x), g(x)\}) = f(x_0) = g(x_0).$$

Hence,

$$\|S_{\phi,1}\|^2 \leq f(x_0) = g(x_0).$$

Then

$$f(x_0) = \frac{a^2 + 1}{2} + \sqrt{(a - x_0)^2 + \left(\frac{a^2 - 1}{2}\right)^2},$$

$$g(x_0) = \frac{b^2 + 1}{2} + \sqrt{(b - x_0)^2 + \left(\frac{b^2 - 1}{2}\right)^2}.$$

Suppose there exists an $\varepsilon > 0$ such that $\|S_{\phi,1}\|^2 \leq f(x_0) - \varepsilon$. Then

$$\left\| \frac{|\phi|^2 + 1}{2} + \sqrt{|\phi - k_0|^2 + \left(\frac{|\phi|^2 - 1}{2}\right)^2} \right\|_\infty \leq \frac{a^2 + 1}{2} + \sqrt{(a - x_0)^2 + \left(\frac{a^2 - 1}{2}\right)^2} - \varepsilon.$$

Since $f(x_0) = g(x_0)$, we have $\|S_{\phi,1}\|^2 \leq g(x_0) - \varepsilon$. Hence,

$$\left\| \frac{|\phi|^2 + 1}{2} + \sqrt{|\phi - k_0|^2 + \left(\frac{|\phi|^2 - 1}{2}\right)^2} \right\|_\infty \leq \frac{b^2 + 1}{2} + \sqrt{(b - x_0)^2 + \left(\frac{b^2 - 1}{2}\right)^2} - \varepsilon.$$

Hence, there exists an $\varepsilon' > 0$ such that

$$|a - k_0| \leq |a - x_0| - \varepsilon' \quad \text{on } E,$$

$$|b - k_0| \leq |b - x_0| - \varepsilon' \quad \text{on } E^c.$$

Since $a < x_0 < b$, we have $|a - x_0| + |b - x_0| = b - a$. If $|a - x_0| \geq |b - x_0|$, then

$$\begin{aligned} & |2|a - x_0|\chi_{E^c} + a - k_0| \\ &= |a\chi_E + (b + |a - x_0| - |b - x_0|)\chi_{E^c} - k_0| \\ &\leq |a - k_0|\chi_E + |b - k_0|\chi_{E^c} + (|a - x_0| - |b - x_0|)\chi_{E^c} \end{aligned}$$

$$\leq |a - x_0| - \varepsilon'.$$

Hence, $\inf\{\|2\chi_{E^c} - k\|_\infty; k \in H^\infty\} < 1$. This is a contradiction (cf. [5, p.198]). If $|a - x_0| \leq |b - x_0|$, then

$$\begin{aligned} & |-2|b - x_0|\chi_E + b - k_0| \\ &= |(a + |a - x_0| - |b - x_0|)\chi_E + b\chi_{E^c} - k_0| \\ &\leq |a - k_0|\chi_E + |b - k_0|\chi_{E^c} + (|b - x_0| - |a - x_0|)\chi_E \\ &\leq |b - x_0| - \varepsilon'. \end{aligned}$$

Hence, $\inf\{\|2\chi_E - k\|_\infty; k \in H^\infty\} < 1$. This is a contradiction (cf. [5, p.198]). These two contradictions imply that ε' must be zero. This contradiction implies that ε must be zero. Hence,

$$\|S_{\phi,1}\|^2 = f(x_0) = g(x_0).$$

This completes the proof.

When a and b are complex numbers, we give Corollary 4. When $|\phi|$ is not constant, Corollary 4 does not contain the completely explicit form of the norm of $S_{\phi,1}$. We need Lemma 2 to prove Corollary 4.

Lemma 2. Let a and b be complex numbers, and let θ be a real number satisfying $\operatorname{Re}(e^{i\theta}(a - b)) = 0$. If the equality

$$\frac{|a|^2 + 1}{2} + \sqrt{|e^{i\theta}a - x|^2 + \left(\frac{|a|^2 - 1}{2}\right)^2} = \frac{|b|^2 + 1}{2} + \sqrt{|e^{i\theta}b - x|^2 + \left(\frac{|b|^2 - 1}{2}\right)^2}$$

holds for some real number x , then $|a| = |b|$ and the equality holds for any real numbers x .

Proof. Suppose the equality holds for some real number x . Then

$$\left\{ \frac{|a|^2 - |b|^2}{2} + \sqrt{|e^{i\theta}a - x|^2 + \left(\frac{|a|^2 - 1}{2}\right)^2} \right\}^2 = |e^{i\theta}b - x|^2 + \left(\frac{|b|^2 - 1}{2}\right)^2.$$

Since $\operatorname{Re}(e^{i\theta}(a-b)) = 0$, we have

$$\begin{aligned} & (|a|^2 - |b|^2) \sqrt{|e^{i\theta}a - x|^2 + \left(\frac{|a|^2 - 1}{2}\right)^2} \\ &= 2\operatorname{Re}(e^{i\theta}(a-b))x + |b|^2 - |a|^2 + \frac{(|b|^2 - |a|^2)(|a|^2 - 1)}{2} \\ &= \frac{(|b|^2 - |a|^2)(|a|^2 + 1)}{2}. \end{aligned}$$

Hence, $|a| = |b|$ and the equality

$$|e^{i\theta}a - x|^2 = |e^{i\theta}b - x|^2$$

holds for any x because $\operatorname{Re}(e^{i\theta}(a-b)) = 0$.

Corollary 4. Let E be a measurable subset of T satisfying $0 < m(E) < 1$, let a and b be complex numbers, and let $\phi = a\chi_E + b\chi_{E^c}$. Then

(1) If θ is a real number satisfying $\operatorname{Re}(e^{i\theta}(a-b)) = 0$, then

$$\|S_{\phi,1}\|^2 \leq \max_{z=a,b} \left\{ \frac{|z|^2 + 1}{2} + \sqrt{(\operatorname{Im}(e^{i\theta}z))^2 + \left(\frac{|z|^2 - 1}{2}\right)^2} \right\}.$$

The equality does not hold in general.

(2) If $|a| = |b|$, then the equality holds for some θ in (1), and

$$\|S_{\phi,1}\|^2 = \frac{|a|^2 + 1}{2} + \sqrt{\left(\frac{|a-b|}{2}\right)^2 + \left(\frac{|a|^2 - 1}{2}\right)^2}.$$

Proof. We prove (2). Suppose $a = b$. Then ϕ becomes a constant function. Hence, by Remark 2,

$$\|S_{\phi,1}\|^2 = \max\{|\phi|^2, 1\} = \max\{|a|^2, 1\} = \frac{|a|^2 + 1}{2} + \sqrt{0 + \left(\frac{|a|^2 - 1}{2}\right)^2}.$$

Suppose $a \neq b$. Since $|\phi| = |a| = |b|$, it follows from Corollary 1 that

$$\|S_{\phi,1}\|^2 = \frac{|a|^2 + 1}{2} + \sqrt{\|H_\phi\|^2 + \left(\frac{|a|^2 - 1}{2}\right)^2}.$$

Let

$$\psi = \frac{2\phi - (a + b)}{a - b}.$$

Then

$$\psi = \begin{cases} 1 & \text{on } E \\ -1 & \text{on } E^c \end{cases}$$

Hence, $\inf\{\|\psi - k\|_\infty; k \in H^\infty\} = 1$ (cf. [5,p.198]). By the Nehari theorem [8],

$$\|H_\phi\| = \inf_{k \in H^\infty} \|\phi - k\|_\infty = \frac{|a - b|}{2}.$$

Hence,

$$\|S_{\phi,1}\|^2 = \frac{|a|^2 + 1}{2} + \sqrt{\left(\frac{|a - b|}{2}\right)^2 + \left(\frac{|a|^2 - 1}{2}\right)^2}.$$

Since $a \neq b$, $|a| = |b|$ and $\operatorname{Re}(e^{i\theta}(a - b)) = 0$, it follows that there exist real numbers u and v such that

$$e^{i\theta}a = u + iv, \quad \text{and} \quad e^{i\theta}b = u - iv.$$

Since $|a| = |b|$, we have

$$\begin{aligned} \left(\frac{|a - b|}{2}\right)^2 &= \frac{|a|^2 - \operatorname{Re}(a\bar{b})}{2} = \frac{u^2 + v^2 - (u^2 - v^2)}{2} \\ &= v^2 = \left(\operatorname{Im}(e^{i\theta}a)\right)^2 = \left(\operatorname{Im}(e^{i\theta}b)\right)^2. \end{aligned}$$

We prove (1). By (2), it is sufficient to prove (1) when $|a| \neq |b|$. We define the functions $f(x)$ and $g(x)$ according to

$$f(x) = \frac{|a|^2 + 1}{2} + \sqrt{|e^{i\theta}a - x|^2 + \left(\frac{|a|^2 - 1}{2}\right)^2},$$

and

$$g(x) = \frac{|b|^2 + 1}{2} + \sqrt{|e^{i\theta}b - x|^2 + \left(\frac{|b|^2 - 1}{2}\right)^2}.$$

Since $|a| \neq |b|$, it follows from Lemma 2 that the equality $f(x) = g(x)$ does not hold for any real number x . If $|a| < |b|$, then $f(x) < g(x)$ because $\operatorname{Re}(e^{i\theta}(a - b)) = 0$. Hence, by Theorem 1,

$$\begin{aligned} \|S_{\phi,1}\|^2 &= \inf_{k \in H^\infty} \left\| \frac{|\phi|^2 + 1}{2} + \sqrt{|\phi - k|^2 + \left(\frac{|\phi|^2 - 1}{2}\right)^2} \right\|_\infty \\ &\leq \inf_{x \in \mathbb{R}} \left\| \frac{|\phi|^2 + 1}{2} + \sqrt{|\phi - e^{-i\theta}x|^2 + \left(\frac{|\phi|^2 - 1}{2}\right)^2} \right\|_\infty \\ &= \inf_{x \in \mathbb{R}} \|f(x)\chi_E + g(x)\chi_{E^c}\|_\infty \leq \inf_{x \in \mathbb{R}} g(x) = g(\operatorname{Re}(e^{i\theta}b)) \\ &= \frac{|b|^2 + 1}{2} + \sqrt{(\operatorname{Im}(e^{i\theta}b))^2 + \left(\frac{|b|^2 - 1}{2}\right)^2}. \end{aligned}$$

Similarly, if $|a| > |b|$, then

$$\|S_{\phi,1}\|^2 \leq \frac{|a|^2 + 1}{2} + \sqrt{(\operatorname{Im}(e^{i\theta}a))^2 + \left(\frac{|a|^2 - 1}{2}\right)^2}.$$

This completes the proof.

3. NORM OF THE OPERATOR INVERSE TO $S_{\alpha,\beta}$

The first author essentially gave Theorem 2 (cf. [7, Corollary 3]). It is not difficult to establish that

$$\inf_{f \in H^2, \|f\|_2=1} \|T_\phi f\|_2^2 \geq \operatorname{ess\,inf}_T (|\phi|^2 - |\phi - k|^2),$$

for any $k \in H^\infty$. The formula of the norm of T_ϕ is as follows.

Theorem 2. Let $\phi \in L^\infty$. Then

$$\inf_{f \in H^2, \|f\|_2=1} \|T_\phi f\|_2^2 = \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T (|\phi|^2 - |\phi - k|^2) \right).$$

The supremum is attained. When T_ϕ is invertible, this is equal to $\|T_\phi^{-1}\|^{-2}$.

Proof. For any $k \in H^\infty$, we define the quantity J_k according to

$$J_k = \operatorname{ess\,inf}_T (|\phi|^2 - |\phi - k|^2).$$

We prove that $\inf\{\|T_\phi f\|_2^2; f \in H^2, \|f\|_2 = 1\} \leq \sup\{J_k; k \in H^\infty\}$. Let $\varepsilon = \inf\{\|T_\phi f\|_2^2; f \in H^2, \|f\|_2 = 1\}$. Then

$$\varepsilon \|f_1\|_2 \leq \|T_\phi f_1\|_2, \quad (f_1 \in H^2).$$

Since $\|T_\phi f_1\|_2^2 + \|H_\phi f_1\|_2^2 = \|\phi f_1\|_2^2$, we have

$$\|H_\phi f_1\|_2^2 \leq \left((|\phi|^2 - \varepsilon^2) f_1, f_1 \right).$$

Let $W_1 = |\phi|^2 - \varepsilon^2$, $W_2 = 1$, $W_3 = \phi$. Since $(\phi f_1, f_2) = (H_\phi f_1, f_2)$, for any $f_1 \in H^2$, $f_2 \in \overline{H_0^2}$, we have

$$(W_1 f_1, f_1) + (W_2 f_2, f_2) + 2\operatorname{Re}(W_3 f_1, f_2)$$

$$\geq \|H_\phi f_1\|_2^2 + \|f_2\|_2^2 + 2\operatorname{Re}(H_\phi f_1, f_2) = \|H_\phi f_1 + f_2\|_2^2 \geq 0,$$

($f_1 \in H^2$, $f_2 \in \overline{H_0^2}$). By the Cotlar-Sadosky lifting theorem [1], $W_1 \geq 0$, $W_2 \geq 0$, and there exists a $k_0 \in H^\infty$ such that

$$|W_3 - k_0|^2 \leq W_1 W_2.$$

Hence,

$$|\phi - k_0|^2 \leq |\phi|^2 - \varepsilon^2.$$

Since $\varepsilon = \inf\{\|T_\phi f\|_2; f \in H^2, \|f\|_2 = 1\}$, we have

$$\inf_{f \in H^2, \|f\|_2=1} \|T_\phi f\|_2^2 \leq J_{k_0} \leq \sup_{k \in H^\infty} J_k.$$

We prove that $\inf\{\|T_\phi f\|_2^2; f \in H^2, \|f\|_2 = 1\} \geq \sup\{J_k; k \in H^\infty\}$. This is the easy direction of the theorem. For any $k \in H^\infty$, $|\phi|^2 - J_k \geq |\phi - k|^2$ and $H_{\phi-k} = H_\phi$. Hence, for any $f_1 \in H^2$,

$$\begin{aligned} \|T_\phi f_1\|_2^2 - J_k \|f_1\|_2^2 &= \|\phi f_1\|_2^2 - \|H_\phi f_1\|_2^2 - J_k \|\phi f_1\|_2^2 \\ &= ((|\phi|^2 - J_k)f_1, f_1) - \|H_\phi f_1\|_2^2 \geq (|\phi - k|^2 f_1, f_1) - \|H_{\phi-k} f_1\|_2^2 \\ &= \|(\phi - k)f_1\|_2^2 - \|H_{\phi-k} f_1\|_2^2 = \|T_{\phi-k} f_1\|_2^2 \geq 0. \end{aligned}$$

Hence, for any $k \in H^\infty$,

$$\|T_\phi f_1\|_2^2 \geq J_k \|f_1\|_2^2, \quad (f_1 \in H^2).$$

Therefore,

$$\sup_{k \in H^\infty} J_k \leq \inf_{f \in H^2, \|f\|_2=1} \|T_\phi f\|_2^2 \leq J_{k_0} \leq \sup_{k \in H^\infty} J_k.$$

Hence the equalities hold, and the infimum is attained by $k = k_0$. This completes the proof.

Corollary 5. If $|\phi|$ is a constant function, then

$$\inf_{f \in H^2, \|f\|_2=1} \|T_\phi f\|_2^2 = |\phi|^2 - \|H_\phi\|^2.$$

Proof. It follows from Theorem 2 that

$$\begin{aligned} \inf_{f \in H^2, \|f\|_2=1} \|T_\phi f\|_2^2 &= \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T (|\phi|^2 - |\phi - k|^2) \right) \\ &= |\phi|^2 + \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T (-|\phi - k|^2) \right) = |\phi|^2 - \inf_{k \in H^\infty} \|\phi - k\|_\infty^2. \end{aligned}$$

By the Nehari theorem [8], this proves the corollary.

Corollary 6. Let $\phi \in L^\infty$. Then

$$\inf_{f \in H^2, \|f\|_2=1} \|T_\phi f\|_2^2 \geq \operatorname{ess\,inf}_T |\phi|^2 - \|H_\phi\|^2.$$

Proof. It follows from the easy direction of Theorem 2 that

$$\begin{aligned} \inf_{f \in H^2, \|f\|_2=1} \|T_\phi f\|_2^2 &\geq \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T (|\phi|^2 - |\phi - k|^2) \right) \\ &\geq \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T |\phi|^2 + \operatorname{ess\,inf}_T (-|\phi - k|^2) \right) \\ &= \operatorname{ess\,inf}_T |\phi|^2 + \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T (-|\phi - k|^2) \right) \\ &= \operatorname{ess\,inf}_T |\phi|^2 - \inf_{k \in H^\infty} \|\phi - k\|_\infty^2. \end{aligned}$$

By the Nehari theorem [8], this proves the corollary.

If $\alpha, \beta \in L^\infty$, then the following inequality is well known and not difficult to establish.

$$\begin{aligned} \inf_{f \in L^2, \|f\|_2=1} \|S_{\alpha,\beta} f\|_2^2 &\leq \operatorname{ess\,inf}_T \left(\min \{ |\alpha|^2, |\beta|^2 \} \right) \\ &= \operatorname{ess\,inf}_T \left(\frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{0 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} \right). \end{aligned}$$

It is not difficult to establish that

$$\begin{aligned} \inf_{f \in L^2, \|f\|_2=1} \|S_{\alpha,\beta} f\|_2^2 \\ \geq \operatorname{ess\,inf}_T \left(\frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} \right), \end{aligned}$$

for any $k \in H^\infty$. The formula of the norm of $S_{\alpha,\beta}^{-1}$ is as follows. The proof of Theorem 3 is essentially the same as the proof of Theorem 1.

Theorem 3. Let $\alpha, \beta \in L^\infty$. Then

$$\inf_{f \in L^2, \|f\|_2=1} \|S_{\alpha,\beta} f\|_2^2 = \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T \left(\frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} \right) \right).$$

The supremum is attained. When $S_{\alpha,\beta}$ is invertible, the supremum is equal to $\|S_{\alpha,\beta}^{-1}\|^{-2}$.

Proof. For any $k \in H^\infty$, we define the quantity N_k according to

$$N_k = \operatorname{ess\,inf}_T \left(\frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} \right).$$

We prove that $\inf\{\|S_{\alpha,\beta} f\|_2^2; f \in L^2, \|f\|_2 = 1\} \leq \sup\{N_k; k \in H^\infty\}$. Let $\varepsilon = \inf\{\|S_{\alpha,\beta} f\|_2; f \in L^2, \|f\|_2 = 1\}$. Then

$$\varepsilon \|f\|_2 \leq \|S_{\alpha,\beta} f\|_2, \quad (f \in L^2).$$

Let $W_1 = |\alpha|^2 - \varepsilon^2$, $W_2 = |\beta|^2 - \varepsilon^2$ and $W_3 = \alpha\bar{\beta} - \varepsilon^2$. Then

$$(W_1 f_1, f_1) + (W_2 f_2, f_2) + 2\operatorname{Re}(W_3 f_1, f_2) \geq 0,$$

($f_1 \in H^2, f_2 \in \overline{H_0^2}$). By the Cotlar-Sadosky lifting theorem [1], $W_1 \geq 0, W_2 \geq 0$, and there exists a $g \in H^\infty$ such that

$$|W_3 - g|^2 \leq W_1 W_2.$$

Hence, $\varepsilon \leq \min\{|\alpha|, |\beta|\}$ and there exists a $g \in H^\infty$ such that

$$|\alpha\bar{\beta} - \varepsilon^2 - g|^2 \leq (|\alpha|^2 - \varepsilon^2) (|\beta|^2 - \varepsilon^2).$$

Let $k_0 = \varepsilon^2 + g$. Then $k_0 \in H^\infty$ and $|\alpha\bar{\beta} - \varepsilon^2 - g| = |\alpha\bar{\beta} - k_0|$. Hence,

$$\begin{aligned} 0 &\leq (|\alpha|^2 - \varepsilon^2) (|\beta|^2 - \varepsilon^2) - |\alpha\bar{\beta} - k_0|^2 \\ &= \varepsilon^4 - (|\alpha|^2 + |\beta|^2) \varepsilon^2 + |\alpha\beta|^2 - |\alpha\bar{\beta} - k|^2. \end{aligned}$$

Suppose

$$\varepsilon^2 \geq \frac{|\alpha|^2 + |\beta|^2}{2} + \sqrt{|\alpha\bar{\beta} - k_0|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2}$$

on some measurable subset E of T . Since

$$\varepsilon^2 \leq \min\{|\alpha|^2, |\beta|^2\} = \frac{|\alpha|^2 + |\beta|^2}{2} - \left|\frac{|\alpha|^2 - |\beta|^2}{2}\right|$$

on T , we have

$$\left|\frac{|\alpha|^2 - |\beta|^2}{2}\right| + \sqrt{|\alpha\bar{\beta} - k_0|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2} \leq 0$$

on E . This implies $|\alpha| - |\beta| = |\alpha\bar{\beta} - k_0| = 0$ on E . Hence,

$$\varepsilon^2 \leq \min\{|\alpha|^2, |\beta|^2\} = \frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{|\alpha\bar{\beta} - k_0|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2}$$

on E . Therefore,

$$\varepsilon^2 \leq \frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{|\alpha\bar{\beta} - k_0|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2}$$

on T . Hence $\varepsilon^2 \leq N_{k_0}$. Since $\varepsilon = \inf\{\|S_{\alpha,\beta}f\|_2; f \in L^2, \|f\|_2 = 1\}$, we have

$$\inf_{f \in L^2, \|f\|_2=1} \|S_{\alpha,\beta}f\|_2^2 \leq N_{k_0} \leq \sup_{k \in H^\infty} N_k.$$

We prove that $\inf\{\|S_{\alpha,\beta}f\|_2^2; f \in L^2, \|f\|_2 = 1\} \geq \sup\{N_k; k \in H^\infty\}$. This is the easy direction of the theorem. For any $k \in H^\infty$, we have

$$(kf_1, f_2) = 0, \quad (f_1 \in H^2, f_2 \in \overline{H_0^2}).$$

Since

$$\frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2} \geq N_k,$$

we have

$$(|\alpha|^2 - N_k)(|\beta|^2 - N_k)$$

$$\begin{aligned}
&\geq \left(\sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} + \frac{|\alpha|^2 - |\beta|^2}{2} \right) \\
&\times \left(\sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} - \frac{|\alpha|^2 - |\beta|^2}{2} \right) \\
&= |\alpha\bar{\beta} - k|^2.
\end{aligned}$$

Hence,

$$\begin{aligned}
&\|\alpha f_1 + \beta f_2\|_2^2 - N_k \|f_1 + f_2\|_2^2 \\
&= \left\| \sqrt{|\alpha|^2 - N_k} f_1 \right\|_2^2 + \left\| \sqrt{|\beta|^2 - N_k} f_2 \right\|_2^2 + 2\operatorname{Re}(\alpha\bar{\beta} f_1, f_2) \\
&\geq 2 \left\| \sqrt{|\alpha|^2 - N_k} f_1 \right\|_2 \left\| \sqrt{|\beta|^2 - N_k} f_2 \right\|_2 + 2\operatorname{Re}((\alpha\bar{\beta} - k) f_1, f_2) \\
&\geq 2 \int_T \left(\sqrt{|\alpha|^2 - N_k} \sqrt{|\beta|^2 - N_k} - |\alpha\bar{\beta} - k| \right) |f_1 f_2| dm \geq 0.
\end{aligned}$$

Hence, for any $k \in H^\infty$,

$$\|S_{\alpha,\beta} f\|_2^2 \geq N_k \|f\|_2^2, \quad (f \in L^2).$$

Therefore,

$$\sup_{k \in H^\infty} N_k \leq \inf_{f \in L^2, \|f\|_2=1} \|S_{\alpha,\beta} f\|_2^2 \leq N_{k_0} \leq \sup_{k \in H^\infty} N_k.$$

Hence the equalities hold, and the infimum is attained by $k = k_0$. This completes the proof.

Remark 3. Let $\alpha, \beta \in L^\infty$, let $\phi = \alpha\bar{\beta}$, and let $\psi = (|\alpha|^2 - |\beta|^2)/2$. Then

$$\inf_{f \in L^2, \|f\|_2=1} \|S_{\alpha,\beta} f\|_2^2 = \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T \left(\sqrt{|\phi|^2 + \psi^2} - \sqrt{|\phi - k|^2 + \psi^2} \right) \right).$$

The supremum is attained. If $|\alpha| = |\beta|$, then $\psi = 0$. Hence

$$\inf_{f \in L^2, \|f\|_2=1} \|S_{\alpha,\beta} f\|_2^2 = \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T (|\phi| - |\phi - k|) \right).$$

Corollary 7. If $|\alpha|$ and $|\beta|$ are constant functions, then

$$\inf_{f \in L^2, \|f\|_2=1} \|S_{\alpha,\beta} f\|_2^2 = \frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{\|H_{\alpha\bar{\beta}}\|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2}.$$

Proof. It follows from Theorem 3 that

$$\begin{aligned} & \inf_{f \in L^2, \|f\|_2=1} \|S_{\alpha,\beta} f\|_2^2 \\ &= \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T \left(\frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2} \right) \right) \\ &= \frac{|\alpha|^2 + |\beta|^2}{2} + \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T \left(-\sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2} \right) \right) \\ &= \frac{|\alpha|^2 + |\beta|^2}{2} + \sup_{k \in H^\infty} \left(-\left\| \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2} \right\|_\infty \right) \\ &= \frac{|\alpha|^2 + |\beta|^2}{2} - \inf_{k \in H^\infty} \left\| \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2} \right\|_\infty \\ &= \frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{\inf_{k \in H^\infty} \|\alpha\bar{\beta} - k\|_\infty^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2}\right)^2}. \end{aligned}$$

By the Nehari theorem [8], this proves the corollary.

Corollary 8. Let $\alpha, \beta \in L^\infty$. Then

$$\inf_{f \in L^2, \|f\|_2=1} \|S_{\alpha,\beta} f\|_2^2 \geq \operatorname{ess\,inf}_T \left(\min\{|\alpha|^2, |\beta|^2\} \right) - \|H_{\alpha\bar{\beta}}\|.$$

Proof. It follows from the easy direction of Theorem 3 that

$$\inf_{f \in L^2, \|f\|_2=1} \|S_{\alpha,\beta} f\|_2^2$$

$$\begin{aligned}
&\geq \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T \left(\frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} \right) \right) \\
&\geq \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T \left(\frac{|\alpha|^2 + |\beta|^2}{2} - |\alpha\bar{\beta} - k| - \left| \frac{|\alpha|^2 - |\beta|^2}{2} \right| \right) \right) \\
&= \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T \left(\min \{ |\alpha|^2, |\beta|^2 \} - |\alpha\bar{\beta} - k| \right) \right) \\
&\geq \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T \left(\min \{ |\alpha|^2, |\beta|^2 \} \right) + \operatorname{ess\,inf}_T \left(-|\alpha\bar{\beta} - k| \right) \right) \\
&= \operatorname{ess\,inf}_T \left(\min \{ |\alpha|^2, |\beta|^2 \} \right) + \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T \left(-|\alpha\bar{\beta} - k| \right) \right) \\
&= \operatorname{ess\,inf}_T \left(\min \{ |\alpha|^2, |\beta|^2 \} \right) + \sup_{k \in H^\infty} \left(-\|\alpha\bar{\beta} - k\|_\infty \right) \\
&= \operatorname{ess\,inf}_T \left(\min \{ |\alpha|^2, |\beta|^2 \} \right) - \inf_{k \in H^\infty} \|\alpha\bar{\beta} - k\|_\infty.
\end{aligned}$$

By the Nehari theorem [8], this proves the corollary.

Remark 4. If $\alpha\bar{\beta} \in H^\infty$, then the supremum in Theorem 3 is attained by $k = \alpha\bar{\beta}$. In this case,

$$\inf_{f \in L^2, \|f\|_2=1} \|S_{\alpha,\beta}f\|_2 = \operatorname{ess\,inf}_T (\min \{ |\alpha|, |\beta| \}).$$

For functions $\alpha, \beta \in L^\infty$, $S_{\alpha,\beta}$ is left invertible if and only if

$$\operatorname{ess\,inf}_T \left(\frac{|\alpha|^2 + |\beta|^2}{2} - \sqrt{|\alpha\bar{\beta} - k|^2 + \left(\frac{|\alpha|^2 - |\beta|^2}{2} \right)^2} \right) > 0,$$

for some $k \in H^\infty$. By Corollary 5, for a function $\phi \in L^\infty$ satisfying $|\phi| = 1$, T_ϕ is left invertible if and only if $S_{\phi,1}$ is left invertible if and only if $\|H_\phi\| < 1$ (cf. [9, p.203]).

Corollary 9. Let $\phi \in L^\infty, |\phi| = 1$. Then

$$\inf_{f \in H^2, \|f\|_2=1} \|T_\phi f\|_2 = \|S_{\phi,1}\| \left(\inf_{f \in L^2, \|f\|_2=1} \|S_{\phi,1}f\|_2 \right).$$

Proof. It follows from Corollary 5 that

$$\inf_{f \in H^2, \|f\|_2=1} \|T_\phi f\|_2^2 = 1 - \|H_\phi\|^2.$$

It follows from Corollary 1 that

$$\|S_{\phi,1}\|^2 = 1 + \|H_\phi\|.$$

It follows from Corollary 7 that

$$\inf_{f \in L^2, \|f\|_2=1} \|S_{\phi,1}f\|_2^2 = 1 - \|H_\phi\|.$$

These equalities proves the corollary.

Corollary 10. If a and b are invertible functions in H^∞ , then

$$\|S_{a,\bar{b}}L_{1/\bar{b}}\|^{-2} = \sup_{k \in H^\infty} \left(\operatorname{ess\,inf}_T \left(\frac{|a|^2 + |b|^2}{2|a|^2} - \sqrt{\left| \frac{\bar{b}}{a} - k \right|^2 + \left(\frac{|a|^2 - |b|^2}{2|a|^2} \right)^2} \right) \right),$$

where $L_{1/\bar{b}}$ denotes the Laurent operator on L^2 . The supremum is attained.

Proof. Since a and b are invertible functions H^∞ , it follows that $S_{\bar{b}/a,1}$ is invertible, and

$$S_{\bar{b}/a,1}^{-1} = S_{a,\bar{b}}L_{1/\bar{b}},$$

(cf. [6, p.88], [10, Theorem 3]). Hence,

$$\|S_{a,\bar{b}}L_{1/\bar{b}}\|^{-2} = \|S_{\bar{b}/a,1}^{-1}\|^{-2} = \inf_{f \in L^2, \|f\|_2=1} \|S_{\bar{b}/a,1}f\|_2^2.$$

By Theorem 3, this proves the corollary.

Acknowledgements. This research was partially supported by Grant-in-Aid for Scientific Research, Ministry of Education.

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