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Multipliers For A Quotient Banach Space And The Nevanlinna-Pick Theorem

By

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Abstract. Let $E$ be a Banach space on a set $X$ and $M(E)$ the space of multipliers of $E$. In this paper, we study the space of multipliers of the quotient space $E/K$ where $K$ is a closed $M(E)$ - invariant subspace in $E$. When $E$ is the classical Hilbert Hardy space, the Nevanlinna and Pick theorem shows $M(E/K)$ is a quotient algebra of $M(E)$. 
§1. Introduction

A Banach space $E$ of functions on a set $X$ is a Banach space whose elements are complex-valued functions defined on $X$ with the usual pointwise addition and scalar multiplication. If $\phi$ is a complex-valued function on $X$ and $\phi f$ belongs to $E$ for all $f$ in $E$, then we write that $\phi$ is an element of $M(E)$, the space of multipliers of $E$. We assume that the point evaluations are continuous on $E$, that is, $X$ is embedded in the dual space $E^*$ and that there is no point in $X$ where all the members of $E$ vanish. It is known that $T_\phi : f \to \phi f$ is a bounded operator on $E$ for each $\phi$ in $M(E)$, since by continuity of point evaluation, each such map has closed graph. $M(E)$ is a closed subalgebra of $B(E)$, the set of bounded operators on $E$, indeed $M(E)$ is closed in the weak operator topology. Thus we assume that the space $M(E)$ of multipliers of $E$ is an operator algebra on $E$.

If $K$ is a closed subspace of $E$ then $E/K$ is also a Banach space. We want to define the space of multipliers $M(E/K)$ of $E/K$. For $\phi$ in $M(E)$ put

$$S_\phi(f + K) = \phi f + K \quad (f \in E).$$

In general, $S_\phi$ is not well defined on $E/K$. We need assume that $M(E)K \subset K$. Suppose $M(E/K) = \{S_\phi; \phi \in M(E)\}$. Then $M(E/K)$ is also an operator algebra on $E/K$. Put

$$\mathcal{K} = \{\phi \in M(E); \phi E \subset K\}$$

then $\mathcal{K}$ is a closed ideal in $M(E)$. By the definition, $S_\phi = 0$ if and only if $\phi E \subset K$. Hence $S_\phi = 0$ if and only if $\phi$ belongs to $\mathcal{K}$. Therefore $S_{\phi + \psi} = S_\phi$ for any $\psi$ in $\mathcal{K}$ and so there exists a one-to-one map from $M(E/K)$ onto $M(E)/\mathcal{K}$. Moreover this map is contractive. In fact, for any $g$ in $K$,

$$S_\phi(f + K) = \phi f + K = \phi(f + g) + K$$

and so

$$\|S_\phi(f + K)\| \leq \|\phi(f + g)\| \leq \|\phi\|\|f + g\|.$$ 

This implies that $\|S_\phi\| \leq \|\phi\|$. Since $S_{\phi + \psi} = S_\phi$ for any $\psi$ in $\mathcal{K}$, $\|S_\phi\| \leq \|\phi + \mathcal{K}\|$. Now the following problem is natural.
Problem 1. Is $M(E/K)$ isometrically isomorphic onto $M(E)/K$?

If Problem 1 can be solved positively, then it shows that $M(E/K)$ is an operator algebra on $E/K$. Suppose

$$M(E/K)' = \{A \in \mathcal{B}(E/K); S_\phi A = AS_\phi \text{ for any } \phi \in M(E)\}.$$  

Then $M(E/K)'$ is a commutative algebra in $\mathcal{B}(E/K)$ which contains $M(E/K)$. We are interested in the following problem.

Problem 2. Is $M(E/K)'$ equal to $M(E/K)$?

Problem 2 is related to a problem of commuting dilation, that is, if $A \in \mathcal{B}(E/K)$ such that $AS_\phi = S_\phi A$ ($\phi \in M(E)$) then does exist $\tilde{A} \in \mathcal{B}(E)$ such that $\tilde{A}T_\phi = T_\phi \tilde{A}$ ($\phi \in M(E)$) and $A(f + K) = \tilde{A}f + K$ ($f \in E$)? If $M(E)' = M(E)$ then $A = T_\psi$ for some $\psi \in M(E)$ and so $A = S_\psi$.

Let $H^p(1 \leq p \leq \infty)$ be the usual Hardy space of analytic functions on the open unit disc $D$. When $E = H^2$, Sarason [4] solved Problems 1 and 2 positively. Then a theorem of Nevanlinna-Pick and a theorem of Carathéodary follow. When $E = H^p$ ($1 \leq p \leq \infty, p \neq 2$) and $K = BH^p$ for a Blaschke product with simple zeros, Snyder [5] solved Problems 1 and 2. In this paper, we solve them when $E = H^p$ ($1 \leq p \leq \infty$) and $K$ is arbitrary.

In general, $M(E)$ may not be a supnorm algebra (see [6]). Even if $E$ is a Hilbert space, $M(E)$ is a supnorm algebra on $X$ and $\dim M(E)/K = 2$, it is known that we can solve negatively Problem 1 for some $E$ and $K$ (see [1]).

In this paper, for a subset $S$ $[S]$ denotes the closed linear span of S.

§2. General case

For each $x$ in $X$, put $\tau_x(f) = f(x)$ for a function $f$ on $X$. We assume that $\tau_x$ is bounded on $E$ and $\|\tau_x\|$ denotes the norm of
$\tau_x$ on $E$. $\tau_x$ is also bounded on $M(E)$ and the norm is just one. For

$$|\tau_x(\phi) \cdot \tau_x(f)| = |\tau_x(\phi f)| \leq \|\tau_x\| \cdot \|\phi\| \cdot \|f\| \quad (\phi \in M(E), f \in E)$$

and so $|\tau_x(\phi) \cdot \|\tau_x\| \leq \|\tau_x\| \cdot \|\phi\|$. Put $E_x = \ker \tau_x \cap E$ and $M(E)_x = \ker \tau_x \cap M(E)$. If $K = \{0\}$ then $\mathcal{K} = \{0\}$ and so Problem 1 can be solved trivially. Moreover the following Proposition 1 solves Problem 2.

**Proposition 1.** If $M(E)_x E$ is dense in $E_x$ for any $x$ in $X$ then $M(E)' = M(E)$.

Proof. It is clear that $M(E) \subset M(E)'$. Suppose $A \in M(E)'$. If $T_{\phi} \in M(E)$ then $T_{\phi} \tau_x = \phi(x)\tau_x$ for any $x \in X$ because $\tau_x \in E^*$. Hence $T^*_{\phi - \phi(x)}(A^* \tau_x) = A^*(T_{\phi - \phi(x)} \tau_x) = 0$ because $AT_{\phi - \phi(x)} = T_{\phi - \phi(x)} A$. Therefore for any $f \in E$, $\langle T_{\phi - \phi(x)} f, A^* \tau_x \rangle = 0$ and so $A^* \tau_x = 0$ on $E_x$ because $M(E)_x E$ is dense in $E_x$.

Thus $A^* \tau_x = \psi(x)\tau_x$ ($x \in X$) and so for any $f \in E$, $\psi(x) f(x) = \langle f, A^* \tau_x \rangle = \langle Af, \tau_x \rangle = \langle Af \rangle(x)$. Hence $Af = \psi f = T\psi f$ ($f \in E$). This implies $A$ belongs to $M(E)$.

**Proposition 2.** If $M(E) + K = E$ then $M(E/K)' = M(E/K)$.

Proof. For any $f \in E$, put $\tilde{f} = f + K$. Then we may assume that $f \in M(E)$ by hypothesis $M(E) + K = E$. For any $g \in M(E)$, if $A \in M(E/K)'$ then for any $x$ in $(E/K)^*$

$$\langle A\tilde{g}, x \rangle = \langle \tilde{g}, A^* x \rangle = \langle \tilde{g} \cdot \tilde{1}, A^* x \rangle$$

$$= \langle ASg\tilde{1}, x \rangle = \langle SgA\tilde{1}, x \rangle = \langle Sg\tilde{\phi}, x \rangle$$

$$= \langle \phi \tilde{g}, x \rangle$$

where $\tilde{\phi} = A\tilde{1}$. Since $M(E) + K = E$, we may assume that $\phi \in M(E)$ and so $A = S\tilde{\phi}$.

For a subset $S$ of $X$, let $E|S$ be the restriction of $E$ to $S$ and put $K = \{f \in E; f = 0$ on $S\}$. Then, $E|S$ becomes a Banach space of functions on $S$ under the quotient norm of $E/K$. We may assume that $E|S \cong E/K$. Put $\mathcal{K} = \{\phi \in M(E); \phi = 0$ on $S\}$, then $M(E)|S \cong M(E)/\mathcal{K}$. Even if $K$ is such a special case, Problems 1 and 2 can not be solved in general. Snyder [5] studied Problem 1,
that is, whether \( M(E)|S = M(E|S) \). In this special case, Problem 1 is just an interpolation problem. That is, if \( f \) is a function on \( S \subset X \) and \( f(E|S) \subset E|S \) then does there exist a function \( F \) on \( X \) such that \( FE \subset E \) and \( F|S = f \) and \( \|F\| = \|f\| \)? Therefore the research of Snyder [5] is contained in our one.

**Corollary 1.** If \( E \) is a commutative Banach algebra with unit then \( M(E/K)' = M(E/K) \).

Proof. If \( E \) is a commutative Banach algebra with unit then \( M(E) = E \) and \( K = K \). Hence \( M(E) + K = E \). Proposition 2 implies that \( M(E/K)' = M(E/K) \).

**Proposition 3.** If \( E \) is a commutative Banach algebra with unit then \( M(E)/K = M(E/K) \) where \( K = K \).

Proof. By the proof of Corollary 1, \( M(E) = E \) and it is easy to see that \( M(E) \) is isometrically isomorphic to \( E \). Similarly \( M(E/K) \) is isometrically isomorphic to \( E/K \). This implies the proposition.

§3. Two dimensional case

In this section we assume that \( M(E) \subset E \). (1) of Theorem 1 is due to Snyder [5] and (2) of Theorem 1 is new.

\( d_x \) is called the derivation at \( x \) if \( d_x(fg) = d_x(f)\tau_x(g) + \tau_x(f)d_x(g) \) \( (f,g \in M(E)) \).

**Proposition 4.** Suppose \( E/K \) and \( M(E/K) \) are of finite dimension 2. Then \( (E/K)^* = [\tau_x, \tau_y] \) for \( x, y \in X \) with \( x \neq y \) or \( (E/K)^* = [\tau_x, d_x] \) for \( x \in X \) where \( d_x \) is a point derivation at \( x \).

Proof. By hypothesis, \( M(E/K) = E/K \) as a set. Since \( M(E/K) \) is a commutative Banach algebra and \( \dim M(E/K) = 2 \), by [2, Proposition 1] it is easy to see that \( M(E/K)^* = [\tau_x, \tau_y] \) for \( x, y \in X \) with \( x \neq y \) or \( M(E/K)^* = [\tau_x, d_x] \) for \( x \in X \).

**Lemma 1.** Suppose \( M(E) + K \) is dense in \( E \). If \( \phi \in M(E) \) then \( S_\phi d_x = \tilde{d}_x(\phi)\tau_x + \tau_x(\phi)d_x \).
Proof. For \( f \in M(E) \)

\[
\langle f + K, S_\phi^*d_x \rangle = \langle \phi f + K, d_x \rangle = \langle \phi f, d_x \rangle \\
= d_x(\phi) \tau_x(f) + \tau_x(\phi)d_x(f) \\
= (f + K, d_x(\phi) \tau_x + \tau_x(\phi)d_x)
\]

**Theorem 1.** Suppose that \( M(E) + K = E \), \( E/K \) and \( M(E/K) \) are of two dimension. If \( M(E/K) \) is isometrically isomorphic to \( M(E)/K \) then the following (1) and (2) are valid.

1. When \((E/K)^* = [\tau_x, \tau_y]\) for \( x, y \in X \) with \( x \neq y \), for given \( u, v \in \mathbb{C} \), there exists \( \phi \in M(E) \) such that \( \tau_x(\phi) = u, \tau_y(\phi) = v \) and \( \| \phi + K \| \leq 1 \) if and only if

\[
\| \alpha \bar{u} \tau_x + \beta \bar{v} \tau_y \|_* \leq \| \alpha \tau_x + \beta \tau_y \|_* \quad (\alpha, \beta \in \mathbb{C}).
\]

2. When \((E/K)^* = [\tau_x, d_x]\) for \( x \in X \), for given \( u, v \in \mathbb{C} \), there exists \( \phi \in M(E) \) such that \( \tau_x(\phi) = u, d_x(\phi) = v \) and \( \| \phi + K \| \leq 1 \) if and only if

\[
\| (\alpha \bar{u} + \beta \bar{v}) \tau_x + \beta \bar{u} d_x \|_* \leq \| \alpha \tau_x + \beta d_x \|_* \quad (\alpha, \beta \in \mathbb{C}).
\]

Proof. (1) If there exists \( \phi \in M(E) \) such that \( \tau_x(\phi) = u, \tau_y(\phi) = v \) with \( \| \phi + K \| \leq 1 \) then \( S_\phi^* \| \leq 1 \) by hypothesis. This implies that

\[
\| \alpha \bar{u} \tau_x + \beta \bar{v} \tau_y \|_* \leq \| \alpha \tau_x + \beta \tau_y \|_* \quad (\alpha, \beta \in \mathbb{C})
\]

because \( S_\phi^* \tau_x = \tau_x(\phi) \tau_x = \bar{u} \tau_x \) and \( S_\phi^* \tau_y = \bar{v} \tau_y \). For the converse, put \( A \in B(H/K) \), \( A^* \tau_x = \bar{u} \tau_x \) and \( A^* \tau_y = \bar{v} \tau_y \), then \( \| A^* \| \leq 1 \) and \( A \) belongs to \( M(E/K)^* \). Since \( M(E) + K = E \), by Proposition 2 \( A = S_\phi \) for some \( \phi \in M(E) \). By hypothesis, \( \| \phi + K \| \leq 1 \) and \( \tau_x(\phi) = u \) and \( \tau_y(\phi) = v \).

(2) If there exists \( \phi \in M(E) \) with \( \tau_x(\phi) = u, d_x(\phi) = v \) with \( \| \phi + K \| \leq 1 \) then \( S_\phi^* \| \leq 1 \) by hypothesis. This and Lemma 1 imply

\[
\| (\alpha \bar{u} + \beta \bar{v}) \tau_x + \beta \bar{u} d_x \|_* \leq \| \alpha \tau_x + \beta d_x \|_* \quad (\alpha, \beta \in \mathbb{C}).
\]
For the converse, put $A \in \mathcal{B}(H/K)$, $A^*\tau_x = \bar{u}\tau_x$ and $A^*d_x = \bar{v}\tau_x + \bar{u}d_x$, then $\|A^*\| \leq 1$ and $A$ belongs to $M(E/K)'$ by Lemma 1. By Proposition 2 $A = S_\phi$ for some $\phi \in M(E)$. By hypothesis, $\|\phi + K\| \leq 1$ and $\tau_x(\phi) = u$ and $\tau_y(\phi) = v$.

In Theorem 1, if (1) or (2) is valid then $M(E/K)$ is isometrically isomorphic to $M(E)/K$.

**Corollary 2.** In Theorem 1, if $E$ is a Hilbert space then there exist $k_x$ and $h_x$ in $E$ such that

$$\tau_x(f) = (f, k_x) \quad (f \in E)$$

and

$$d_x(f) = (f, h_x) \quad (f \in E)$$

and the following (1) and (2) are valid.

1. When $(E/K)^* = [\tau_x, \tau_y]$ for $x, y \in X$ with $x \neq y$, for given $u, v \in \mathbb{C}$, there exists $\phi \in M(E)$ such that $\tau_x(\phi) = u, \tau_y(\phi) = v$ and $\|\phi + K\| \leq 1$ if and only if

$$|\alpha|^2(1 - |u|^2)(k_x, k_x) + \alpha\beta(1 - \bar{u}v)(k_x, k_y) + \bar{\alpha}\beta(1 - u\bar{v})(k_y, k_x) + |\beta|^2(1 - |v|^2)(k_y, k_y) \geq 0$$

for any $\alpha, \beta \in \mathbb{C}$.

2. When $(E/K)^* = [\tau_x, d_x]$ for $x \in X$, for given $u, v \in \mathbb{C}$, there exists $\phi \in M(E)$ such that $\tau_x(\phi) = u, d_x(\phi) = v$ and $\|\phi + K\| \leq 1$ if and only if

$$(|\alpha|^2 - |\alpha\bar{u} + |\beta|^2\bar{u}v|^2)(k_x, k_x) + (\alpha\beta - (\alpha|u|^2 + |\beta|^2u\bar{v}))(k_x, h_x) + (\bar{\alpha}\beta - (\bar{\alpha}|u|^2 + |\beta|^2\bar{u}v))(h_x, k_x) + |\beta|^2(1 - |u|^2)(h_x, h_x) \geq 0$$

for any $\alpha, \beta \in \mathbb{C}$.

The condition of (1) in Corollary 2 shows that the $2 \times 2$ matrix \{(1 - |u|^2)(k_x, k_x), (1 - \bar{u}v)(k_x, k_y), (1 - u\bar{v})(k_y, k_x), (1 - |v|^2)(k_y, k_y)\} is nonnegative. When $(k_x, h_x) = 0$, the condition of (2) in Corollary 2 shows that the $2 \times 2$ matrix \{(1 - |u|^2)(k_x, k_x), \bar{u}v(h_x, k_x), u\bar{v}(k_x, h_x), (1 - |u|^2 - |v|^2)(h_x, h_x)\} is nonnegative.
When \( \dim E/K \geq 3 \), even if \( \dim E/K \) is finite, it is difficult to describe \((E/K)^*\) except \( K = \{ f \in E : f(x_j) = 0 \ 1 \leq j \leq \dim E/K \} \) and \( x_i \neq x_j (i \neq j) \). Therefore we could not generalize (2) of Theorem 1.

§4. Hardy space \( H^p \) \((1 \leq p \leq \infty)\)

In this section, we solve Problems 1 and 2 when \( E = H^p \) for \( 1 \leq p \leq \infty \). When \( E = H^\infty \), we can solve trivially Problems 1 and 2 by Corollary 2 and Proposition 4. If \( \dim H^p/K < \infty \) then \( M(H^p) + K = H^p \) and so \( M(H^p/K)' = M(H^p/K) \) by Proposition 2. However we have to work more in order to prove \( M(H^p/K) = M(H^p)/K \).

Let \( W \) be a nonnegative function in \( L^1 \) with \( \log W \) in \( L^1 = L^1(d\theta/2\pi) \). Then there exists an outer function \( h \) in \( H^1 \) with \( W = |h| \). For \( 1 \leq p < \infty \), \( H^p(W) \) denotes the closure of analytic polynomials in \( L^p(W) = L^1(Wd\theta/2\pi) \). Then \( H^p(W) = h^{-1/p}H^p \) and so we may assume that \( H^p(W) \) is a Banach space of analytic functions on \( D \). It is known that the point evaluations of points in \( D \) are continuous on \( H^p(W) \). It is well known that \( M(H^p(W)) = H^\infty \).

**Theorem 2.** For \( 1 \leq p \leq \infty \), let \( K \) be a closed subspace of \( H^p(W) \) with \( M(H^p(W))/K \subseteq K \). Then \( M(H^p(W))/K' = M(H^p(W)/K) \) and \( M(H^p(W)/K) = M(H^p(W))/\mathcal{K} \) where \( \mathcal{K} = \{ \psi \in M(H^p(W)) : \psi \mathcal{H}^p(W) \subseteq K \} \).

**Proof.** Since \( M(H^p(W)) = H^\infty \), \( K = QH^\infty \) for some inner function and \( K = QH^p(W) \). Since \( M(H^p(W)/K) \subseteq M(H^p(W)/K)' \), we will show that \( M(H^p(W)/K)' \subseteq M(H^p(W)/K) \). If \( A \in M(H^p(W)/K)' \) then there exists \( \psi \in H^p(W) \) such that \( A(1+K) = \psi + K \). For any polynomial \( f = h^{-1/p}F \) in \( H^p(W) \), \( \| \psi f + K \|_W \leq \| A \| \| f + K \|_W \).

Since \( K = QH^p(W) = h^{-1/p}QH^p \), if \( 1/p + 1/q = 1 \)

\[
\| \psi f + QH^p(W) \|_W = \sup \{ |\langle \psi f, g \rangle_W| : g \in \{ QH^p(W) \}^\perp \text{ and } \| g \|_W \leq 1 \}
\]

\[
= \sup \left\{ \left| \int \psi h^{-1/p}F\overline{Q}h^{-1/q}G |h|dm \right| : G \in H^q_0 \text{ and } \| G \|_q \leq 1 \right\}
\]
\[ = \sup \left\{ \left| \int \psi \bar{Q} G d\theta \right| : G \in H_0^q \text{ and } \|G\|_q \leq 1 \right\} \]
\[ \leq \|A\| \|f\|_w = \|A\| \|F\|_p \]

because \( \{QH^p(W)\}^\perp = Q\bar{h}^{1/p}|h|^{-1} \bar{H}_0^p \). Thus

\[ \sup \left\{ \left| \int \psi \bar{Q} F G d\theta / 2\pi \right| : F \in H^p, G \in H_0^q, \|F\|_p \leq 1 \text{ and } \|G\|_q \leq 1 \right\} \leq \|A\| \]

By the factorization theorem of \( H^1 \),

\[ \sup\left\{ \left| \int \psi \bar{Q} K d\theta / 2\pi \right| : K \in H_0^1 \text{ and } \|K\|_1 \leq 1 \right\} \leq \|A\| \]

Since \((\bar{Q}H_0^1)^* = L^\infty/QH^\infty\), \(\|\psi + QH^\infty\| \leq \|A\|\). Hence there exists a function \( \phi \) in \( H^\infty \) such that \( S_\phi = A \) and \( \|\phi + K\| = \|S_\phi\| \).

Thus \( A \) belongs to \( M(H^p(W)/K) \). Therefore \( M(H^p(W)/K)' = M(H^p(W)/K) \) and \( M(H^p(W)/K) = M(H^p(W)/K) \).

**Corollary 3.** For \( 1 \leq p \leq \infty \), \( M(H^p(W)/QH^p(W)) = H^\infty/QH^\infty \) for any inner function \( Q \).
References


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