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Shift Operators on the \mathbb{C}^2 -valued Hardy Space

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Abstract

In this paper, we study closed invariant subspaces under the action of a unilateral shift and a truncated shift in the Hardy space that takes values in a two dimensional Hilbert space. We deal with characteristic functions, unitary equivalence and C^* -algebras on these spaces.

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0 Introduction

In the classical Hardy space theory on the unit disk, A. Beurling proved that every submodule, which is a closed invariant subspace under multiplication operators by bounded analytic functions, is characterized by an inner function in [5]. This result is very important for the structure theory of a single operator on a Hilbert space (cf. [11]), so that many researchers have studied submodules in other Hilbert function spaces. However, the general structure of submodules is extremely complicated in multivariables. Recent development and an extensive list of references concerning this topic can be found in [7].

In this paper, we study closed invariant subspaces under the action of a unilateral shift and a truncated shift in the Hardy space that takes values in a two dimensional Hilbert space. We call such an invariant subspace a submodule for short. Although this topic is very restricted, the authors consider that this research will help us to understand the general structure of submodules in the Hardy space over the bidisk. Because, the Hardy space over the bidisk can be regarded as the limit of the tensor product Hilbert space of the classical Hardy space H^2 and the n dimensional Hilbert space \mathbb{C}^n as n tends to infinity in the weak topology. More precisely, the \mathbb{C}^2 -valued Hardy space $H^2 \otimes \mathbb{C}^2$

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can be identified with the quotient module $(H^2 \otimes H^2)/w^2(H^2 \otimes H^2)$, and $H^2 \otimes H^2$ is actually equal to the Hardy space over the bidisk with variables z and w . We also want to emphasize that some difficulties in general cases appear in this two dimensional setting, and our results can be generalized easily to the case where n is any positive integer.

Section 1 is the preliminaries, in which we introduce notions used in this paper and translate well known results on the Sz.-Nagy-Foiaş characteristic function into our setting. In Section 2, we obtain a Beurling type theorem under some condition. In Section 3, we focus on some properties of row operators whose entries are Toeplitz operators. In Section 4, we discuss unitary equivalence on submodules, and obtain a result similar to Agrawal-Clark-Douglas theorem given in [1]. In Section 5, we deal with an example in detail. Submodules of finite codimension are described in Section 6. In Section 7, isomorphisms of the C^* -algebras generated by the operators defined by module multiplication on submodules are considered.

1 Preliminaries

Let \mathbb{C} denote the complex plane, and let \mathbb{D} denote the open unit disk in \mathbb{C} , that is, $\mathbb{D} = \{\lambda \in \mathbb{C} : |\lambda| < 1\}$. If \mathcal{H} is a Hilbert space, then $H^2(\mathcal{H})$ denotes the \mathcal{H} -valued Hardy space over \mathbb{D} . An \mathcal{H} -valued function f belongs to $H^2(\mathcal{H})$ if and only if f is analytic in \mathbb{D} and

$$\|f\|^2 := \sup_{0 \leq r < 1} \frac{1}{2\pi} \int_0^{2\pi} \|f(re^{i\theta})\|^2 d\theta < +\infty.$$

In other words, $H^2(\mathcal{H})$ is the tensor product Hilbert space of the classical Hardy space $H^2 = H^2(\mathbb{C})$ and \mathcal{H} . Let T_z be the Toeplitz operator of the coordinate function z , and let S be the truncated shift operator on \mathbb{C}^2 which maps $(1, 0)$ to $(0, 1)$ and $(0, 1)$ to $(0, 0)$. Then $H^2(\mathbb{C}^2)$ has a module structure over the commutative algebra generated by T_z and S by the usual action of operators.

Definition 1.1 *A closed subspace \mathcal{M} of $H^2(\mathbb{C}^2)$ is called a submodule if \mathcal{M} is invariant under the action of operators T_z and S .*

Let V_z (resp. R) denote the restriction of T_z (resp. S) on a submodule \mathcal{M} , that is, $V_z = T_z|_{\mathcal{M}}$ (resp. $R = S|_{\mathcal{M}}$). Then V_z commutes with R on \mathcal{M} .

If \mathcal{M} is a submodule of $H^2(\mathbb{C}^2)$, then by the Kolmogorov-Wold decomposition, we have

$$\mathcal{M} = \sum_{n \geq 0} \oplus T_z^n (\mathcal{M} \ominus T_z \mathcal{M}).$$

Hence \mathcal{M} can be identified with $H^2(\mathcal{D})$, where we set $\mathcal{D} = \mathcal{M} \ominus T_z \mathcal{M}$. It is easy to check that $\dim \mathcal{D} \leq 2$. We define an operator $\Omega(\zeta)$ from \mathcal{D} to \mathbb{C}^2 for ζ a.e. in $\mathbb{T} = \partial\mathbb{D}$ as

follows:

$$\Omega(\zeta)d := d(\zeta),$$

where d is in \mathcal{D} . Then we can define an operator valued function Ω which maps the function $z^j \otimes d$ in $H^2(\mathcal{D})$ to a function in $H^2(\mathbb{C}^2)$ as follows:

$$\Omega(\zeta) ((z^j \otimes d)(\zeta)) = \Omega(\zeta)\zeta^j d = \zeta^j d(\zeta),$$

a.e. on \mathbb{T} , where d is in \mathcal{D} and $j \geq 0$. Then Ω has the following properties:

- (i) Ω can be extended analytically to \mathbb{D} ,
- (ii) $\Omega^*(\zeta)\Omega(\zeta) = I_{\mathcal{D}}$ a.e. on \mathbb{T} ,
- (iii) $\mathcal{M} = \Omega H^2(\mathcal{D})$.

Let U be an isometry from \mathcal{D} to \mathbb{C}^2 . Then there exists an operator valued function Θ defined by the following commutative diagram:

$$\begin{array}{ccc} \mathcal{D} & \xrightarrow{\Omega(\zeta)} & \mathbb{C}^2 \\ U \downarrow & & \parallel \\ \mathbb{C}^2 & \xrightarrow{\Theta(\zeta)} & \mathbb{C}^2. \end{array}$$

Moreover Θ is a partial isometry valued function having the following properties:

- (i) Θ can be extended analytically to \mathbb{D} ,
- (ii) $\Theta^*(\zeta)\Theta(\zeta)$ is the orthogonal projection onto $U\mathcal{D}$ a.e. on \mathbb{T} ,
- (iii) $\mathcal{M} = \Theta H^2(\mathbb{C}^2)$.

This Θ is called the characteristic function of \mathcal{M} in the sense of Sz.-Nagy and Foiaş [11], which is determined uniquely up to unitary matrices. Moreover Θ has a matrix representation depending on U . The entries of Θ are Toeplitz operators of bounded analytic functions on \mathbb{D} , that is,

$$\Theta = \begin{pmatrix} T_{\theta_{11}} & T_{\theta_{12}} \\ T_{\theta_{21}} & T_{\theta_{22}} \end{pmatrix},$$

where every θ_{ij} is a bounded analytic function on \mathbb{D} . Hence it follows that $\text{tr } \Theta$ and $\det \Theta$ are bounded analytic functions. It is easy to check the following:

- (i) if $\dim \mathcal{D} = 2$, then $\det \Theta$ is an inner function,
- (ii) For any d in \mathcal{D} , entries of d are bounded analytic functions.

2 A Beurling type theorem

In this section, we consider the condition that V_z^* commutes with R . This condition is similar to that in Mandrekar [9] and Nakazi [10].

Theorem 2.1 V_z^* commutes with R if and only if Θ has one of the following matrix representations:

$$\Theta = \begin{pmatrix} T_q & 0 \\ 0 & T_q \end{pmatrix} \quad \text{or} \quad \Theta = \begin{pmatrix} 0 & 0 \\ T_q & 0 \end{pmatrix},$$

where q is an inner function on \mathbb{D} .

Proof It is easy to show the ‘‘if’’ part. We show the ‘‘only if’’ part. We suppose that V_z^* commutes with R , which implies that \mathcal{D} is invariant under R . Let d be a normalized vector in $\mathcal{D} \ominus R\mathcal{D}$. Then d is orthogonal to Rd .

First, we show that $\dim \mathcal{D} \ominus R\mathcal{D} = 1$. Let f be an element in $\mathcal{D} \ominus R\mathcal{D}$ orthogonal to d , and let $S^{(1)}$, $S^{(0)}$ and $S^{(-1)}$ denote S , $I_{\mathcal{M}}$ and S^* , respectively. Then

$$\int_{\mathbb{T}} \langle f(\zeta), S^{(n)}d(\zeta) \rangle \zeta^k |d\zeta| = 0,$$

for any integer k and $n = -1, 0, 1$. Since d is a non-zero vector, we have $f = 0$.

(Case 1. $Rd \neq 0$)

Let $d_1 = d$ and $d_2 = Rd/\|Rd\|$. We define a unitary operator U from \mathcal{D} onto \mathbb{C}^2 as follows:

$$U : \begin{aligned} d_1 &\mapsto e_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \\ d_2 &\mapsto e_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}. \end{aligned}$$

Next we show that Θ commutes with S .

$$\begin{aligned} S\Theta(\zeta) : \begin{pmatrix} f(\zeta) \\ g(\zeta) \end{pmatrix} &\mapsto S\Omega(\zeta)(f(\zeta)d_1 \oplus g(\zeta)d_2) = f(\zeta)d_2(\zeta), \\ \Theta(\zeta)S : \begin{pmatrix} f(\zeta) \\ g(\zeta) \end{pmatrix} &\mapsto \Omega(\zeta)(f(\zeta)d_2) = f(\zeta)d_2(\zeta). \end{aligned}$$

Therefore Θ commutes with S on $H^2(\mathbb{C}^2)$. Hence Θ can be represented by the following Toeplitz form:

$$\Theta = \begin{pmatrix} T_{\theta_1} & 0 \\ T_{\theta_2} & T_{\theta_1} \end{pmatrix}.$$

Since $\Theta(\zeta)$ is an isometry a.e. on \mathbb{T} , its column vectors are orthogonal. Hence

$$\theta_2(\zeta)\overline{\theta_1(\zeta)} = 0.$$

Since every θ_i is bounded analytic, we have $\theta_1 = 0$ or $\theta_2 = 0$. Hence we have $\theta_2 = 0$ by the assumption $Rd \neq 0$.

(Case 2. $Rd = 0$) We define an isometry from \mathcal{D} to \mathbb{C}^2 as follows:

$$U : d \mapsto e_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}.$$

Then it is easy to check that $\Theta S = S\Theta = 0$. Therefore Θ has a Toeplitz form. Moreover, the assumption $Rd = 0$ implies that $R\mathcal{M} = S\mathcal{M} = \{0\}$. Then, by the Beurling theorem, there exists an inner function q such that

$$\mathcal{M} = \begin{pmatrix} 0 \\ qH^2(\mathbb{C}) \end{pmatrix}.$$

Hence we have

$$\Theta = \begin{pmatrix} 0 & 0 \\ T_q & 0 \end{pmatrix}.$$

This completes the proof.

Remark 2.1 In this remark, we suppose that $\dim \mathcal{D} = 1$. Then we have the complete description of \mathcal{M} . Indeed, Let $d = (d_1, d_2)$ be a normalized vector in \mathcal{D} . Then, for an isometry U which maps d to $(1, 0)$, we have

$$\Theta = \begin{pmatrix} T_{d_1} & 0 \\ T_{d_2} & 0 \end{pmatrix}.$$

Therefore

$$\mathcal{M} = \{(d_1 f, d_2 f) : f \in H^2\}.$$

However \mathcal{M} is invariant under S . It follows that $d_1 = 0$. Hence we have

$$\Theta = \begin{pmatrix} 0 & 0 \\ T_{d_2} & 0 \end{pmatrix}.$$

That is, if $\dim \mathcal{D} = 1$ then $\mathcal{M} = \{0\} \oplus qH^2$ for some inner function q . Hence we have the following:

Theorem 2.2 *Let \mathcal{M} be a submodule. Then $\dim \mathcal{D} = 1$ if and only if there exists an inner function q such that $\mathcal{M} = \{0\} \oplus qH^2$.*

Corollary 2.1 *If $\dim \mathcal{D} = 1$, then $[V_z^*, R] = 0$.*

3 Submodules and row operators

We consider general cases where $\dim \mathcal{D} = 2$. Then the characteristic function Θ of a submodule \mathcal{M} takes values in unitary matrices on \mathbb{C}^2 . The matrix representation of Θ is uniquely determined up to unitary matrices on \mathbb{C}^2 . In this section, we focus on the following observation:

Since \mathcal{M} is invariant under S , for any f_1 and f_2 in H^2 , there exist functions g_1 and g_2 in H^2 such that

$$S\Theta \begin{pmatrix} f_1 \\ f_2 \end{pmatrix} = \Theta \begin{pmatrix} g_1 \\ g_2 \end{pmatrix}.$$

It follows that

$$\begin{pmatrix} 0 \\ \theta_{11}f_1 + \theta_{12}f_2 \end{pmatrix} = \begin{pmatrix} \theta_{11}g_1 + \theta_{12}g_2 \\ \theta_{21}g_1 + \theta_{22}g_2 \end{pmatrix}, \quad (3.1)$$

where each θ_{ij} is an entry of Θ . Let T_j denote the operator from $H^2 \oplus H^2$ to H^2 defined as follows:

$$T_j : \begin{pmatrix} f_1 \\ f_2 \end{pmatrix} \mapsto \theta_{j1}f_1 + \theta_{j2}f_2.$$

Then (3.1) is equivalent to the following:

$$\text{Im } T_1 \subseteq T_2(\ker T_1). \quad (3.2)$$

Note that $\ker T_j$ includes the following non trivial vector space for each j :

$$\{(-\theta_{j2}h, \theta_{j1}h) : h \in H^2\}.$$

It is easy to show the following:

- (i) $\ker T_1$ is invariant under T_z in $H^2(\mathbb{C}^2)$,
- (ii) $\text{Im } T_1$ and $T_2(\ker T_1)$ are invariant under T_z in H^2 ,
- (iii) the closure of $T_2(\ker T_1)$ includes $(\det \Theta)H^2$.

Let $\mathcal{M}_j = \mathcal{M}(\theta_{j1}, \theta_{j2})$ denote the submodule generated by θ_{j1} and θ_{j2} in H^2 , that is, \mathcal{M}_j is the closure of the subspace $\{\theta_{j1}f + \theta_{j2}g : f, g \in H^2\}$. Then there exists an inner function q_j such that $\mathcal{M}_j = q_j H^2$ by Beurling's theorem. Since $q_1 H^2 \subseteq q_2 H^2$ by (3.2), it follows that q_2 is a divisor of q_1 . Hence Θ can be decomposed as follows:

$$\Theta = \begin{pmatrix} T_{q_1} & 0 \\ 0 & T_{q_2} \end{pmatrix} \begin{pmatrix} T_{\eta_{11}} & T_{\eta_{12}} \\ T_{\eta_{21}} & T_{\eta_{22}} \end{pmatrix},$$

where q_1 is divided by q_2 and $\mathcal{M}(\eta_{j1}, \eta_{j2}) = H^2$ for every j . We note that inner functions q_1 and q_2 are uniquely determined by \mathcal{M} up to constants in \mathbb{T} .

Proposition 3.1 *Let \mathcal{M} be a submodule of $H^2(\mathbb{C}^2)$ with $\dim \mathcal{D} = 2$, and let $\Theta = (T_{\theta_{ij}})$ be the characteristic function of \mathcal{M} . Then row operators $T_1 = (T_{\theta_{11}} \ T_{\theta_{12}})$ and $T_2 = (T_{\theta_{21}} \ T_{\theta_{22}})$ satisfy the following two conditions:*

- (i) *the pair of row operators (T_1, T_2) is a joint isometry, that is, $T_1^* T_1 + T_2^* T_2 = I$,*
- (ii) *$\text{Im } T_1 \subseteq T_2(\ker T_1)$.*

Conversely if two row operators $T_1 = (T_{\theta_{11}} \ T_{\theta_{12}})$ and $T_2 = (T_{\theta_{21}} \ T_{\theta_{22}})$ whose entries are Toeplitz operators of bounded analytic functions satisfy the above conditions (i) and (ii), then the range of the operator matrix $(T_{\theta_{ij}})$ is a submodule in $H^2(\mathbb{C}^2)$ with $\dim \mathcal{D} = 2$.

4 Unitary equivalence

In this section, we classify submodules in the sense of unitary equivalence. If \mathcal{H} is a Hilbert space, then $L^2(\mathcal{H})$ denotes the Hilbert space consisting of \mathcal{H} -valued square integrable functions with respect to the normalized Lebesgue measure $d\theta/2\pi$ on \mathbb{T} . Then it is easy to check that a co-isometric extension of V_z on a submodule \mathcal{M} of $H^2(\mathbb{C}^2)$ is the multiplication operator by z on $L^2(\mathbb{C}^2)$.

Definition 4.1 *Two submodules \mathcal{M} and $\tilde{\mathcal{M}}$ are said to be unitarily equivalent as modules if there exists a unitary operator W from \mathcal{M} onto $\tilde{\mathcal{M}}$ such that $\tilde{V}_z W = W V_z$ and $\tilde{R} W = W R$, where \tilde{V}_z and \tilde{R} denote restrictions of T_z and S on $\tilde{\mathcal{M}}$, respectively. Then the above W is called a unitary module map from \mathcal{M} onto $\tilde{\mathcal{M}}$.*

Lemma 4.1 *If two submodules \mathcal{M} and $\tilde{\mathcal{M}}$ are unitarily equivalent as modules, then $\dim \mathcal{D} = \dim \tilde{\mathcal{D}}$, where we set $\tilde{\mathcal{D}} = \tilde{\mathcal{M}} \ominus z\tilde{\mathcal{M}}$.*

Proof Let W be a unitary module map from \mathcal{M} onto $\tilde{\mathcal{M}}$. Then it is easy to show that $W(\mathcal{M} \ominus z\mathcal{M}) = \tilde{\mathcal{M}} \ominus z\tilde{\mathcal{M}}$.

By Theorem 2.2 and Lemma 4.1, it suffices to consider unitary equivalence only on submodules with $\dim \mathcal{D} = 2$.

Theorem 4.1 *If two submodules \mathcal{M} and $\tilde{\mathcal{M}}$ with $\dim \mathcal{D} = 2$ are unitarily equivalent as modules by a unitary module map W , then there exists a unimodular Borel function u on \mathbb{T} such that*

$$W = \begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix},$$

where we identified a bounded Borel function u with its multiplication operator.

Proof First, we note that W intertwines V_z and \tilde{V}_z , that is, $WV_z = \tilde{V}_zW$. By the commutant lifting theorem ([11]), there exists an operator X which commutes with the multiplication by z on $L^2(\mathbb{C}^4) = L^2(\mathbb{C}^2) \oplus L^2(\mathbb{C}^2)$ and agrees with W on \mathcal{M} , that is,

$$\begin{aligned} X : \mathcal{M} \oplus \{0\} &\rightarrow \{0\} \oplus \tilde{\mathcal{M}} \\ f \oplus 0 &\mapsto 0 \oplus Wf \end{aligned}$$

for any f in \mathcal{M} . Then each entry of X is a multiplication operator by a bounded Borel function. We set

$$X = \begin{pmatrix} * & * \\ U & * \end{pmatrix} \text{ and } U = \begin{pmatrix} u_{11} & u_{12} \\ u_{21} & u_{22} \end{pmatrix}.$$

Next, we show that $u_{11} = u_{22}$ and $u_{12} = 0$. Since

$$\begin{aligned} WS &: \begin{pmatrix} f \\ g \end{pmatrix} \mapsto \begin{pmatrix} u_{12}f \\ u_{22}f \end{pmatrix} \\ SW &: \begin{pmatrix} f \\ g \end{pmatrix} \mapsto \begin{pmatrix} 0 \\ u_{11}f + u_{12}g \end{pmatrix} \end{aligned}$$

and W commutes with S on \mathcal{M} , we have $u_{12}f = 0$ and $u_{22}f = u_{11}f + u_{12}g$ for any (f, g) in \mathcal{M} . Since entries of elements of \mathcal{M} are in H^2 , we have that $u_{12} = 0$ and $u_{11} = u_{22}$.

Lastly, we show $u_{21} = 0$. We note that there exists an inner function q_1 such that $\mathcal{M}(\theta_{11}, \theta_{12}) = q_1H^2$, and $S\mathcal{M}$ is dense in $\{(0, q_1f) : f \in H^2\}$. Since W is a unitary module map from \mathcal{M} onto $\tilde{\mathcal{M}}$, we have

$$\|f\| = \|q_1f\| = \left\| \begin{pmatrix} u_{11} & 0 \\ u_{21} & u_{11} \end{pmatrix} \begin{pmatrix} 0 \\ q_1f \end{pmatrix} \right\| = \left\| \begin{pmatrix} 0 \\ u_{11}q_1f \end{pmatrix} \right\| = \|u_{11}q_1f\|,$$

for any vector $(0, q_1f)$ in \mathcal{M} . Hence $u_{11}q_1$ is an isometry as a multiplication operator on H^2 , that is, $u_{11}q_1$ is inner. Hence u_{11} is a unimodular function. Further, we have

$$\begin{aligned} \|q_1f\|^2 + \|q_2g\|^2 &= \left\| \begin{pmatrix} u_{11} & 0 \\ u_{21} & u_{11} \end{pmatrix} \begin{pmatrix} q_1f \\ q_2g \end{pmatrix} \right\|^2 \\ &= \left\| \begin{pmatrix} u_{11}q_1f \\ u_{21}q_1f + u_{11}q_2g \end{pmatrix} \right\|^2 = \|u_{11}q_1f\|^2 + \|u_{21}q_1f + u_{11}q_2g\|^2, \end{aligned}$$

for any (q_1f, q_2g) in \mathcal{M} . Hence we have $\|q_2g\| = \|u_{21}q_1f + u_{11}q_2g\|$. Therefore we have $2\|q_2g\| \geq \|u_{21}q_1f\|$. If u_{21} were not the zero function, then $\ker T_2$ would be a subspace of $\ker T_1$. However $\ker T_2$ is not the null space and $\Theta = (\theta_{ij})$ is isometric by the assumption $\dim \mathcal{D} = 2$. This is a contradiction. Hence $u_{21} = 0$. This concludes the proof.

We shall give two criterions of unitary equivalence of submodules as corollaries of Theorem 4.1. To begin, we note the following basic fact as a lemma:

Lemma 4.2 *Let \mathcal{M} and $\tilde{\mathcal{M}}$ be submodules with $\dim \mathcal{D} = 2$. If they are unitarily equivalent as modules by a unitary module map W , then $W\Theta$ is the characteristic function of $\tilde{\mathcal{M}}$.*

Proof Trivially, $W\Theta$ is an isometry from $H^2(\mathbb{C}^2)$ onto $\tilde{\mathcal{M}}$. We note that $(W\Theta)(\zeta) = W(\zeta)\Theta(\zeta)$ for ζ a.e. in \mathbb{T} . Further, $W\Theta$ can be extended analytically to \mathbb{D} , and it is easy to show that $((W\Theta)(\zeta))^* ((W\Theta)(\zeta)) = I_{\mathbb{C}^2}$.

For a submodule $\tilde{\mathcal{M}}$, we use the notations $\tilde{\Theta}$, \tilde{T}_1 , \tilde{q}_1 and \tilde{q}_2 defined by $\tilde{\mathcal{M}}$, as in the case of \mathcal{M} .

Corollary 4.1 *Suppose that \mathcal{M} and $\tilde{\mathcal{M}}$ are two submodules in $H^2(\mathbb{C}^2)$. If they are unitarily equivalent as modules, then $\tilde{q}_1/q_1 = \tilde{q}_2/q_2$.*

Proof By Theorem 4.1 and Lemma 4.2, we have the conclusion.

Corollary 4.2 *If \mathcal{M} and $\tilde{\mathcal{M}}$ are unitarily equivalent as modules, then there exists a unitary matrix V in $M_2(\mathbb{C})$ such that $V \ker T_1 = \ker \tilde{T}_1$.*

Proof Suppose that $\mathcal{M} = \Theta H^2(\mathbb{C}^2)$ and $\tilde{\mathcal{M}} = \tilde{\Theta} H^2(\mathbb{C}^2)$ are unitarily equivalent as modules by a unitary module map W . Then, by Theorem 4.1 and Lemma 4.2, there exist a bounded Borel function u on \mathbb{T} and a constant unitary matrix V such that

$$W\Theta = \begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix} \Theta = \tilde{\Theta}V.$$

First, we suppose that (f, g) is in $\ker \tilde{T}_1$. Then

$$\tilde{\Theta} \begin{pmatrix} f \\ g \end{pmatrix} = \begin{pmatrix} 0 \\ * \end{pmatrix}.$$

Since $W\Theta V^* = \tilde{\Theta}$, we have $T_1 V^*(f, g) = 0$. Hence we have $\ker \tilde{T}_1 \subseteq V \ker T_1$.

Conversely, if (f, g) is in $V \ker T_1$, then we have

$$\Theta V^* \begin{pmatrix} f \\ g \end{pmatrix} = \begin{pmatrix} 0 \\ * \end{pmatrix}.$$

Since $W\Theta V^* = \tilde{\Theta}$, we have $\tilde{T}_1(f, g) = 0$. Hence we have $V \ker T_1 \subseteq \ker \tilde{T}_1$. This concludes the proof.

5 Example: the submodule generated by $(z, -1)$

In this section, we deal with an example. Let \mathcal{M} be the submodule generated by $(z, -1)$. Then, by some calculations, we have $\mathcal{D} = \vee\{(1/\sqrt{2})(z, -1), (1/\sqrt{2})(z^2, z)\}$. Hence we have the following matrix representation of the characteristic function Θ of \mathcal{M} with respect to the canonical orthonormal basis $(1, 0)$ and $(0, 1)$ of \mathbb{C}^2 :

$$\Theta = \frac{1}{\sqrt{2}} \begin{pmatrix} T_z & T_z^2 \\ -1 & T_z \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} T_z & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & T_z \\ -1 & T_z \end{pmatrix}.$$

By Corollaries 4.1 and 4.2, we have that the following three submodules

$$\frac{1}{\sqrt{2}} \begin{pmatrix} T_z & T_z^2 \\ -1 & T_z \end{pmatrix} H^2(\mathbb{C}^2), \begin{pmatrix} T_z & 0 \\ 0 & 1 \end{pmatrix} H^2(\mathbb{C}^2) \text{ and } H^2(\mathbb{C}^2)$$

are mutually different in the sense of unitary equivalence, that is, they are not unitarily equivalent as modules.

However there exists a module map, which is not unitary, from $H^2(\mathbb{C}^2)$ onto \mathcal{M} . Indeed, closed subspaces $\{(0, zf) : f \in H^2\}$ and $\{(zf, -f) : f \in H^2\}$ are contained in \mathcal{M} . Hence we have

$$\mathcal{M} = \{(zf, -f + zg) : f, g \in H^2\} = \Delta H^2(\mathbb{C}^2),$$

where Δ is the following operator matrix:

$$\Delta = \begin{pmatrix} T_z & 0 \\ -1 & T_z \end{pmatrix}.$$

We note that Δ is a module map from $H^2(\mathbb{C}^2)$ onto \mathcal{M} , that is, Δ commutes with T_z and S on $H^2(\mathbb{C}^2)$. Moreover Δ has the left inverse as follows:

$$\begin{pmatrix} T_z^* & 0 \\ T_z^{*2} & T_z^* \end{pmatrix} \begin{pmatrix} T_z & 0 \\ -1 & T_z \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

6 Submodules of finite codimension

In this section, we study submodules of finite codimension in $H^2(\mathbb{C}^2)$.

Theorem 6.1 *Let \mathcal{M} be a submodule in $H^2(\mathbb{C}^2)$. Then the following three assertions are equivalent:*

- (i) \mathcal{M} is generated by some non-zero vectors whose entries are polynomials,
- (ii) \mathcal{M} is of finite codimension in $H^2(\mathbb{C}^2)$,

(iii) *there exists a finite Blaschke product q such that \mathcal{M} contains $qH^2(\mathbb{C}^2)$.*

Proof First, we show (i) \Rightarrow (ii). It suffices to assume that \mathcal{M} is generated by a vector (p_1, p_2) where p_1 and p_2 are polynomials. Let \mathcal{N} denote the orthogonal complement of \mathcal{M} in $H^2(\mathbb{C}^2)$. If a vector (x, y) is in \mathcal{N} , then the following equations hold for any h in H^2 :

$$\begin{aligned} \left\langle \begin{pmatrix} x \\ y \end{pmatrix}, \begin{pmatrix} p_1 h \\ p_2 h \end{pmatrix} \right\rangle &= \langle x, p_1 h \rangle + \langle y, p_2 h \rangle = 0 \\ \left\langle \begin{pmatrix} x \\ y \end{pmatrix}, \begin{pmatrix} 0 \\ p_1 h \end{pmatrix} \right\rangle &= \langle y, p_1 h \rangle = 0. \end{aligned}$$

Hence we have that $T_{p_1}^* x + T_{p_2}^* y = 0$ and y is orthogonal to $p_1 H^2$ in H^2 . Let $(p_1 H^2)^\perp$ denote the orthogonal complement of $p_1 H^2$ in H^2 . Then x belongs to the vector space

$$\mathcal{X} := (T_{p_1}^*)^{-1} (\{-T_{p_2}^* y : y \in (p_1 H^2)^\perp\}).$$

Hence we have that \mathcal{N} is contained in $\mathcal{X} \times (p_1 H^2)^\perp$. Since p_1 is a polynomial and \mathcal{X} is orthogonal to $p_1^2 H^2$, we have that the dimension of $\mathcal{X} \times (p_1 H^2)^\perp$ is finite.

Next, we show (ii) \Rightarrow (iii). For any bounded analytic function φ , S_φ will denote the operator defined as follows: $S_\varphi f = P_{\mathcal{N}} \varphi f$ for any f in \mathcal{N} . Since \mathcal{N} is of finite dimension, there exists a polynomial p such that $S_p = p(S_z) = 0$. Let q be the inner factor of p . Then q is a finite Blaschke product and $S_q = 0$. Hence $q\mathcal{N}$ is a subspace of \mathcal{M} . Further, \mathcal{M} is invariant under T_q . Therefore $qH^2(\mathbb{C}^2)$ is contained in \mathcal{M} .

Lastly, we show (iii) \Rightarrow (i). Let q be a finite Blaschke product. Since \mathcal{M} is invariant under multiplications by bounded analytic functions, $qH^2(\mathbb{C}^2)$ is generated by some vectors whose entries are polynomials. Hence, it suffices to show that entries of every element in $H^2(\mathbb{C}^2) \ominus qH^2(\mathbb{C}^2)$ are rational functions whose poles are not in \mathbb{D} . Let (x, y) be in $H^2(\mathbb{C}^2) \ominus qH^2(\mathbb{C}^2)$. Then the following equations hold for any f and g in H^2 :

$$\left\langle \begin{pmatrix} x \\ y \end{pmatrix}, \begin{pmatrix} qf \\ qg \end{pmatrix} \right\rangle = \langle x, qf \rangle + \langle y, qg \rangle = 0.$$

Hence x and y are orthogonal to qH^2 , that is, x and y are rational functions whose poles are not in \mathbb{D} .

Remark 6.1 Theorem 6.1 should be compared with the following facts in Hardy spaces:

- In the classical Hardy space, a submodule is generated by polynomials if and only if it is of finite codimension. This is known as Kronecker's theorem.
- In the Hardy space over the bidisk, there exist submodules which are generated by polynomials and of infinite codimension (cf. [2]).

7 C^* -algebras on submodules

Let \mathfrak{T} denote the Toeplitz algebra. Then the C^* -algebra generated by T_z and S is the tensor product C^* -algebra of \mathfrak{T} and $M_2(\mathbb{C})$. $\mathfrak{A}(\mathcal{M})$ will denote the C^* -algebra generated by V_z and R in the algebra of all bounded linear operators on \mathcal{M} .

Definition 7.1 *For two submodules \mathcal{M}_1 and \mathcal{M}_2 in $H^2(\mathbb{C}^2)$, two C^* -algebras $\mathfrak{A}(\mathcal{M}_1)$ and $\mathfrak{A}(\mathcal{M}_2)$ are said to be unitarily equivalent if there exists a unitary operator U from \mathcal{M}_1 onto \mathcal{M}_2 such that $U\mathfrak{A}(\mathcal{M}_1)U^* = \mathfrak{A}(\mathcal{M}_2)$.*

Trivially, if two submodules are unitarily equivalent as modules, then their C^* -algebras are unitarily equivalent. Furthermore, it is not difficult to see that C^* -algebras on submodules given in Section 5 are unitarily equivalent to $\mathfrak{A}(H^2(\mathbb{C}^2))$, so it will be natural that one asks the following question:

Question For any submodule \mathcal{M} with $\dim \mathcal{D} = 2$, is $\mathfrak{A}(\mathcal{M})$ unitarily equivalent to $\mathfrak{A}(H^2(\mathbb{C}^2))$?

We will give a negative answer to this question, that is, we will see that there exist submodules whose C^* -algebras are not unitarily equivalent to $\mathfrak{A}(H^2(\mathbb{C}^2))$. In order to deal with this problem, we need several lemmas.

Lemma 7.1 *If a submodule \mathcal{M} is an orthogonal direct sum of two submodules \mathcal{M}_1 and \mathcal{M}_2 in $H^2(\mathbb{C}^2)$, then $\mathcal{M}_1 = \{0\}$ or $\mathcal{M}_2 = \{0\}$.*

Proof Let $f_j = (f_{1j}, f_{2j})$ be an element in \mathcal{M}_j for $j = 1, 2$. Then, for any non-negative integers k and l , we have

$$\int_{\mathbb{T}} (f_{11}\overline{f_{12}} + f_{21}\overline{f_{22}})\zeta^{k-l} |d\zeta| = \langle T_z^k f_1, T_z^l f_2 \rangle = 0,$$

$$\int_{\mathbb{T}} f_{11}\overline{f_{22}}\zeta^{k-l} |d\zeta| = \langle T_z^k S f_1, T_z^l f_2 \rangle = 0$$

and

$$\int_{\mathbb{T}} f_{21}\overline{f_{12}}\zeta^{k-l} |d\zeta| = \langle T_z^k f_1, T_z^l S f_2 \rangle = 0.$$

It follows that $f_{11}\overline{f_{12}} + f_{21}\overline{f_{22}} = 0$, $f_{11}\overline{f_{22}} = 0$ and $f_{21}\overline{f_{12}} = 0$ on \mathbb{T} . Since every f_{ij} belongs to H^2 , $f_{ij}(\zeta)$ does not take zero a.e. on \mathbb{T} . Hence we have $f_1 = 0$ or $f_2 = 0$. This concludes the proof.

Lemma 7.2 *Let \mathcal{M} be a submodule in $H^2(\mathbb{C}^2)$. Then $\mathfrak{A}(\mathcal{M})$ contains the ideal of all compact operators on \mathcal{M} .*

Proof Since $\mathfrak{A}(\mathcal{M})$ is irreducible by Lemma 7.1 and contains a non-zero finite rank operator $[V_z^*, V_z]$, we have the conclusion.

Let $C(X)$ be the C^* -algebra of all continuous functions defined on a compact subset X of \mathbb{C} , let $M_2(C(\mathbb{T}))$ denote the two-by-two matrix algebra whose entries are functions in $C(\mathbb{T})$, and \mathfrak{K} be the ideal of all compact operators. For an inner function q , X_q denotes the set of all ζ in \mathbb{T} such that q can not be extended analytically from \mathbb{D} to ζ .

Lemma 7.3 *Let q be an inner function. If $\mathcal{M} = qH^2 \oplus H^2$, then $\mathfrak{A}(\mathcal{M})/\mathfrak{K}$ is isomorphic to $M_2(C(\mathbb{T})) \oplus C(X_q)$, where we set $C(X_q) = \{0\}$ if X_q is the empty set.*

Proof Since $\mathcal{M} = qH^2 \oplus H^2 = qH^2 \oplus qH^2 \oplus K(q)$ where we set $K(q) = H^2 \ominus qH^2$, V_z and R have the following matrix representation:

$$V_z = \begin{pmatrix} V_z & 0 & 0 \\ 0 & V_z & A \\ 0 & 0 & S_z \end{pmatrix} \text{ and } R = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \text{ on } qH^2 \oplus qH^2 \oplus K(q).$$

Then it is easy to show that the above operator A has rank one. Therefore we have

$$V_z \equiv \begin{pmatrix} V_z & 0 & 0 \\ 0 & V_z & 0 \\ 0 & 0 & S_z \end{pmatrix} \pmod{\mathfrak{K}}.$$

Further, $C^*(S_z)/\mathfrak{K}$ is isomorphic to $C(X_q)$ by Arveson's theorem in [4], where $C^*(S_z)$ is the C^* -algebra generated by S_z and the identity operator on $K(q)$. Hence $\mathfrak{A}(\mathcal{M})/\mathfrak{K}$ is isomorphic to $M_2(C(\mathbb{T})) \oplus C(X_q)$. This completes the proof.

Lemma 7.4 *Set $Q_j = M_2(C(\mathbb{T})) \oplus C(X_j)$ for $j = 1, 2$. Then Q_1 and Q_2 are isomorphic if and only if X_1 and X_2 are homeomorphic.*

Proof The “if” part is trivial. We show the “only if” part. Assume that there exists a $*$ -isomorphism φ from Q_1 onto Q_2 . It suffices to show that the restriction of φ on $\{0\} \oplus C(X_1)$ induces a $*$ -isomorphism from $C(X_1)$ onto $C(X_2)$.

First, we show that $\varphi(M_2(C(\mathbb{T})) \oplus \{0\}) = M_2(C(\mathbb{T})) \oplus \{0\}$. Let e_{ij}^k denote the matrix unit whose non-zero entry is z^k for $1 \leq i, j \leq 2$ and $k \in \mathbb{Z}$. Then, for $i \neq j$, $\varphi(e_{ij}^k \oplus 0)$ is in $M_2(C(\mathbb{T})) \oplus \{0\}$, because $e_{ij}^k \oplus 0$ is nilpotent. Since $\{e_{ij}^k : 1 \leq i, j \leq 2, i \neq j, k \in \mathbb{Z}\}$ generates $M_2(C(\mathbb{T})) \oplus \{0\}$ as C^* -algebras, we have $\varphi(M_2(C(\mathbb{T})) \oplus \{0\}) \subseteq M_2(C(\mathbb{T})) \oplus \{0\}$. Similarly we have that $\varphi^{-1}(M_2(C(\mathbb{T})) \oplus \{0\}) \subseteq M_2(C(\mathbb{T})) \oplus \{0\}$. Therefore we have that

$$\varphi(M_2(C(\mathbb{T})) \oplus \{0\}) = M_2(C(\mathbb{T})) \oplus \{0\}. \quad (7.1)$$

Next we show that $\varphi(\{0\} \oplus C(X_1)) = \{0\} \oplus C(X_2)$. For any f in $C(X_1)$, we set $\varphi(0 \oplus f) = A \oplus g \in M_2(C(\mathbb{T})) \oplus C(X_2)$. Then $(e_{ij} \oplus 0)(A \oplus g)(e_{kl} \oplus 0) = (e_{ij} \oplus 0)\varphi(0 \oplus f)(e_{kl} \oplus 0) = 0$ by (7.1). Therefore we have that $\varphi(\{0\} \oplus C(X_1)) \subseteq \{0\} \oplus C(X_2)$. Similarly, we have that $\varphi^{-1}(\{0\} \oplus C(X_2)) \subseteq \{0\} \oplus C(X_1)$. This completes the proof.

Now we are in a position to prove the main theorem of this section.

Theorem 7.1 *Set $\mathcal{M}_1 = q_{11}H^2 \oplus q_{12}H^2$ and $\mathcal{M}_2 = q_{21}H^2 \oplus q_{22}H^2$ where q_{j1} and q_{j2} are inner functions such that q_{j1} is divisible by q_{j2} for each $j = 1, 2$. Then two C^* -algebras $\mathfrak{A}(\mathcal{M}_1)$ and $\mathfrak{A}(\mathcal{M}_2)$ are unitarily equivalent if and only if $X_{q_{11}/q_{12}}$ and $X_{q_{21}/q_{22}}$ are homeomorphic.*

Proof Without loss of generality, we may assume that q_{12} and q_{22} are constant, and we set $q_1 = q_{11}$ and $q_2 = q_{21}$, for short. Then the “only if” part is immediate from Lemmas 7.3 and 7.4. We show the “if” part, that is, we assume that X_{q_1} and X_{q_2} are homeomorphic. First, we mention the fact that S_z which appeared in the proof of Lemma 7.3 is the sum of a normal operator and a compact operator, which was first proved by Ahern and Clark in [3]. Hence, without loss of generality, we may assume that $X_{q_1} = X_{q_2}$ by the standard spectral theory. Further, using the BDF theory (cf. [6] and [8]), it follows that there exists a unitary operator U_0 from $K(q_1)$ onto $K(q_2)$ such that $U_0 S_z^{(1)} U_0^* \equiv S_z^{(2)} \pmod{\mathfrak{K}}$, where $S_z^{(j)}$ denotes S_z acting on $K(q_j)$. Setting

$$U = \begin{pmatrix} T_{q_2} T_{q_1}^* & 0 & 0 \\ 0 & T_{q_2} T_{q_1}^* & 0 \\ 0 & 0 & U_0 \end{pmatrix},$$

then U is a unitary operator from \mathcal{M}_1 onto \mathcal{M}_2 , and it is easy to check that the following:

$$U \begin{pmatrix} V_z^{(1)} & 0 & 0 \\ 0 & V_z^{(1)} & 0 \\ 0 & 0 & S_z^{(1)} \end{pmatrix} U^* \equiv \begin{pmatrix} V_z^{(2)} & 0 & 0 \\ 0 & V_z^{(2)} & 0 \\ 0 & 0 & S_z^{(2)} \end{pmatrix} \pmod{\mathfrak{K}}$$

and

$$U \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} U^* \equiv \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \pmod{\mathfrak{K}}.$$

Therefore we have that $U\mathfrak{A}(\mathcal{M}_1)U^* = \mathfrak{A}(\mathcal{M}_2)$ by Lemma 7.2. This completes the proof.

Corollary 7.1 *There exist submodules whose C^* -algebras are not unitarily equivalent to $\mathfrak{A}(H^2(\mathbb{C}^2))$.*

Remark 7.1 With a little more effort, one can prove that the two zero sets of quotients of inner functions are actually equal if and only if the C^* -algebras are isomorphic using a map which extends the identification of module multiplication.

Remark 7.2 The proof of Theorem 7.1 can be applied to general cases in $n \geq 3$. Then the corresponding statement is as follows: Set $\mathcal{M}_1 = q_{11}H^2 \oplus \cdots \oplus q_{1n}H^2$ and $\mathcal{M}_2 = q_{21}H^2 \oplus \cdots \oplus q_{2n}H^2$ where q_{ij} 's are inner functions such that q_{ij} is divisible by $q_{i,j+1}$ for each $i = 1, 2$ and $j = 1, 2, \dots, n-1$. Then two C^* -algebras $\mathfrak{A}(\mathcal{M}_1)$ and $\mathfrak{A}(\mathcal{M}_2)$ are unitarily equivalent if and only if $X_{q_{1j}/q_{1,j+1}}$ and $X_{q_{2j}/q_{2,j+1}}$ are homeomorphic for every $j = 1, 2, \dots, n-1$.

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