Title	Finite rank intermediate Hankel operators on the Bergman space
Author(s)	Nakazi, T.; Osawa, T.
Citation	Hokkaido University Preprint Series in Mathematics, 437, 1-16
Issue Date	1998-11-1
DOI	10.14943/83583
Doc URL	http://hdl.handle.net/2115/69187
Type	bulletin (article)
File Information	pre437.pdf

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Series #437. November 1998

HOKKAIDO UNIVERSITY
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Finite Rank Intermediate Hankel Operators On The Bergman Space

by

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

1991 Mathematics Subject Classification : Primary 47 B 35.

Key words and phrases : Hankel operator, finite rank, Bergman space

Abstract. Let $L^2 = L^2(D, rdrd\theta/\pi)$ be the Lebesgue space on the open unit disc and $L^2_a = L^2 \cap \mathcal{H}ol(D)$ be the Bergman space. Let P be the orthogonal projection of L^2 onto L^2_a and let Q be the orthogonal projection onto $\bar{L}^2_{a,0} = \{g \in L^2 \; ; \; \bar{g} \in L^2_a, \; g(0) = 0\}$. Then $I - P \geq Q$. The big Hankel operator and the small Hankel operator on L^2_a are defined as the following : For ϕ in L^∞, $H^{big}_\phi(f) = (I - P)(\phi f)$ and $H^{small}_\phi(f) = Q(\phi f)$ $(f \in L^2_a)$. In this paper, the finite rank intermediate Hankel operators between H^{big}_ϕ and H^{small}_ϕ are studied. We are working on the more general space, that is, the weighted Bergman space.

§1. Introduction

Let D be the open unit disc in $\mathbf{C}$ and $d\mu$ the finite positive Borel measure on D. Let $L^2 = L^2(\mu) = L^2(D, d\mu)$ and $\mathcal{H}ol(D)$ be the set of all holomorphic functions on D. The weighted Bergman space $L_a^2 = L_a^2(\mu)$ is the intersection of L^2 and $\mathcal{H}ol(D)$. In general, L_a^2 is not closed. In [6, Theorem 8], when (supp $\mu) \cap D$ is a uniqueness set for $\mathcal{H}ol(D)$, the first author and M.Yamada gave a necessary and sufficient condition for that L_a^2 is closed. Throughout this paper, we assume that L_a^2 is closed. When $d\mu = rdrd\theta/\pi$, L_a^2 is the usual Bergman space.

For μ such that $L_a^2(\mu)$ is closed, when $\mathcal{M}$ is the closed subspace of $L^2(\mu)$ and $z\mathcal{M} \subseteq \mathcal{M}$, $\mathcal{M}$ is called an invariant subspace. Suppose $\mathcal{M} \supseteq zL_a^2$. $P^{\mathcal{M}}$ denotes the orthogonal projection from L^2 onto $\mathcal{M}$. For ϕ in $L^\infty = L^\infty(\mu) = L^\infty(D, d\mu)$, the intermediate Hankel operator $H_\phi^{\mathcal{M}}$ is defined by

$$H_\phi^{\mathcal{M}} f = (I - P^{\mathcal{M}})(\phi f) \quad (f \in L_a^2).$$

When $\mathcal{M} = L_a^2$, $H_\phi^{\mathcal{M}}$ is called a big Hankel operator H_ϕ^{big} and when $\mathcal{M} = (\bar{z}\bar{L}_a^2)^\perp$, $H_\phi^{\mathcal{M}}$ is called a small Hankel operator H_ϕ^{small}. Note that $H_\phi^{\mathcal{M}}$ is called a little Hankel operator when $\mathcal{M} = (\bar{L}_a^2)^\perp$.

For arbitrary symbol ϕ in L^∞, in the case of $d\mu = rdrd\theta/\pi$, both H_ϕ^{big} and H_ϕ^{small} were studied when they are compact operators or Schatten class operators (see [12]). However it seems to have not been studied when they are finite rank operators. When $\bar{\phi}$ is in L_a^2, it is known (see [12, p155]) that if H_ϕ^{big} is a finite rank operator then $H_\phi^{big} = 0$ and if $\bar{\phi}$ is a polynomial then H_ϕ^{small} is a finite rank operator. In this paper, for arbitrary symbol ϕ in L^∞ we show that if H_ϕ^{big} is a finite rank operator then $H_\phi^{big} = 0$, and we study when H_ϕ^{small} is a finite rank operator. In fact, we study such problems for the intermediate Hankel operators $H_\phi^{\mathcal{M}}$ on the weighted Bergman space $L_a^2(\mu)$. In [2],[7],[9] and [10], intermediate Hankel operators were studied in special weights, $d\mu = (\alpha+1)(1-r^2)^\alpha rdrd\theta/\pi$ for $-1 < \alpha < \infty$. In particular, E.Strose [9] studied finite rank intermediate Hankel operators.

Let $d\mu = d\sigma(r)d\theta$ be a Borel measure on D where $d\sigma(r)$ is a positive measure on [0,1) with $d\sigma([0,1)) = 1/2\pi$ and $d\theta$ is the Lebesgue measure on ∂D. $L_a^2(\mu)$ is closed if $d\sigma([t,1)) > 0$ for any $t > 0$ (see [6]). For this type measures, it is possible to study more precisely the intermediate Hankel operators. In fact, L^2 has the following orthogonal decomposition :

$$L^2 = \sum_{j=-\infty}^{\infty} \oplus \mathcal{L}^2 e^{ij\theta}$$

where $\mathcal{L}^2 = L^2(d\sigma) = L^2([0,1), d\sigma)$. Set

$$\mathbf{H}^2 = \sum_{j=0}^{\infty} \oplus \mathcal{L}^2 e^{ij\theta},$$

then $L_a^2 \subset \mathbf{H}^2 \subset (\bar{z}\bar{L}_a^2)^\perp$ and $L^2 = \mathbf{H}^2 \oplus e^{-i\theta}\bar{\mathbf{H}}^2$. If $\mathcal{M} = \mathbf{H}^2$, it is easy comparatively to determine finite rank Hankel operators $H_\phi^{\mathcal{M}}$ and we can do it completely in Section 5.

We can expect that $H_\phi^{\mathcal{M}}$ is close to H_ϕ^{big} in case $\mathcal{M} \subseteq \mathbf{H}^2$ (see Section 5) and $H_\phi^{\mathcal{M}}$ is close to H_ϕ^{small} in case $\mathcal{M} \supseteq \mathbf{H}^2$ (see Section 6).

In Section 2, we will describe an invariant subspace in L_a^2 whose codimension is of finite. Moreover we will show that there does not exist an invariant subspace which contains L_a^2 properly and in which L_a^2 is of finite codimension. We will also give a lot of examples of invariant subspaces which contain L_a^2 and in which Hankel operators will studied in this paper. In Section 3, we will describe finite rank intermediate Hankel operators for arbitrary measure μ such that $L_a^2(\mu)$ is closed. Moreover we will show that there does not exist any nonzero finite rank Hankel operators $H_\phi^{big}$and there exists a nonzero finite rank Hankel operator H_ϕ^{small}. In fact, we will give two necessary and sufficient conditions for that if $H_\phi^{\mathcal{M}}$ is of finite rank $\leq \ell$ then $H_\phi^{\mathcal{M}} = 0$. In Sections 3,4 and 5 we will use the Fourier coefficients $\{\mathcal{M}_j\}_{j=-\infty}^{\infty}$ of $\mathcal{M}$ and so we will assume $d\mu = d\sigma(r)d\theta$. Using the Fourier coefficients of ϕ and $\mathcal{M}$, we will give a necessary and sufficient condition for that $H_\phi^{\mathcal{M}}$ is of finite rank $\leq \ell$. Assuming that ϕ is a harmonic function, we can get a better necessary and sufficient condition. When $\mathcal{M} \subseteq \mathbf{H}^2$, using the Fourier coefficients $\{\mathcal{M}_j\}_{j=-\infty}^{\infty}$, we will give a necessary condition and a sufficient condition for that if $H_\phi^{\mathcal{M}}$ is of finite rank $\leq \ell$ then $H_\phi^{\mathcal{M}} = 0$. Two conditions are very similar but are a little different. Applications will be given to examples in Section 2.

§2. Invariant subspaces

In this section, we assume that $d\mu = d\sigma(r)d\theta$ and $d\sigma([t,1)) > 0$ for any $t > 0$, except Propositions 1 and 2. For our purpose, the invariant subspace $\mathcal{M}$ must contain zL_a^2 but $\ker H_\phi^{\mathcal{M}}$ is an invariant subspace in L_a^2. If $H_\phi^{\mathcal{M}}$ is of finite rank, then the codimension of $\ker H_\phi^{\mathcal{M}}$ in L_a^2 is finite. In order to study finite rank intermediate Hankel operators, we need the generalization of a result of S.Axler and P.Bourdon [1] which determins finite codimensional invariant subspaces in L_a^2 when $d\mu = rdrd\theta/\pi$. In the following Propositions 1 and 2, the measure μ is an arbitrary finite positive Borel measure such that L_a^2 is closed and $(supp\mu) \cap D$ is a uniqueness set for $\mathcal{H}ol(D)$. Since $\mathbf{H}^2 \cap L^\infty$ is an extended weak-$*$Dirichlet algebra in L^∞, Proposition 4 is a corollary of [4, Theorem 1]. We will give several examples of invariant subspaces which contain zL_a^2.

Proposition 1. *Suppose $\mathcal{M}$ is an invariant subspace in L_a^2 and ℓ is a positive integer. The codimension of $\mathcal{M}$ in L_a^2 is ℓ if and only if $\mathcal{M} = qL_a^2$ where $q = \prod_{j=1}^{\ell}(z - a_j)$ and $a_j \in D$ $(1 \leq j \leq \ell)$.*

Proof. The proof is almost parallel to that in [1, Theorem 1]. We will give a sketch of it. Suppose $\mathcal{M}^\perp = L_a^2 \ominus \mathcal{M}$ and $\dim \mathcal{M}^\perp = \ell$. Put

$$S_z f = P(zf) \quad (f \in \mathcal{M}^\perp)$$

where P is an orthogonal projection. Since $\ell < \infty$, there exists an analytic polynomial b such that $b(S_z) = S_{b(z)} = 0$ and the degree of b is less than equal to ℓ. Hence $b\mathcal{M}^\perp \subseteq \mathcal{M}$ and so $bL_a^2 \subseteq \mathcal{M}$. We will show that the zeros of b are only in D and the degree of $b = \ell$. Then $\mathcal{M} = bL_a^2$. It is clear that the degree of $b = \ell$. In this direction, we needed not the condition such that $(supp\mu) \cap D$ is a uniqueness set.

If $a \notin D$, $(z-a)L_a^2$ is dense in L_a^2. For, assuming $a \geq 1$ and so $a = 1$ without a loss of generality, if $\varepsilon > 0$ then $(z-1)L_a^2 = (z-1)\{z-(1+\varepsilon)\}^{-1}L_a^2$. For any $f \in L_a^2$, it is easy to see that

$$\int_D |\frac{z-1}{z-(1+\varepsilon)}f - f|^2 d\mu \to 0 \quad (\varepsilon \to 0).$$

This implies that $(z-1)L_a^2$ is dense in L_a^2. Thus all zeros of b must be in D. The 'if' part is clear because any point $a \in D$ gives a bounded evaluation functional. Here we used the condition such that $(supp\mu) \cap D$ is a uniqueness set (*see* [6, (1) of Theorem 8]).

Proposition 2. *Suppose that $(z-a)^{-1}$ does not belong to L^2 for each $a \in D$. If $\mathcal{M}$ is an invariant subspace which contains L_a^2 properly, then the codimension of L_a^2 in $\mathcal{M}$ is infinite.*

Proof. If $\dim \mathcal{M} \ominus L_a^2 = \ell < \infty$, by the proof of Proposition 1, there exists a polynomial $b = \prod_{j=1}^{\ell}(z-a_j)$ such that $b\mathcal{M} \subseteq L_a^2$ and $a_j \in D$ $(1 \leq j \leq \ell)$. Hence there exists a function ϕ in $\mathcal{M}$ such that $\phi \notin L_a^2$ and $g = b\phi \in L_a^2$. If $g(a_k) \neq 0$ for some k, then $g/(z-a_k) = \phi\prod_{j\neq k}(z-a_j)$ can not belong to L^2 because $(z-a_k)^{-1} \notin L^2$. Hence $g(a_j) = 0$ for any j. By [6, the proof in (1) of Theorem 8], $g \in bL_a^2$ and so $\phi = g/b$ belongs to L_a^2. This contradiction implies that $\dim \mathcal{M} \ominus L_a^2 = \infty$.

For an invariant subspace $\mathcal{M}$, set

$$\mathcal{M}_j = \{f_j \in \mathcal{L}^2 \ ; \ f \in \mathcal{M},\ f(z) = \sum_{j=-\infty}^{\infty} f_j(r)e^{ij\theta}\}.$$

Then $\mathcal{M}_j$ is a subspace in $\mathcal{L}^2$, $r\mathcal{M}_j \subseteq \mathcal{M}_{j+1}$ and hence $\dim \mathcal{M}_{j+1} \geq \dim \mathcal{M}_j$. We call $\{\mathcal{M}_j\}_{j=-\infty}^{\infty}$ the Fourier coefficients of $\mathcal{M}$. $\mathcal{M}_je^{ij\theta}$ may not belong to $\mathcal{M}$. If $\mathcal{M}_je^{ij\theta}$ belongs to $\mathcal{M}$ for any j, then $\mathcal{M}$ has the following decomposition :

$$\mathcal{M} = \sum_{j=-\infty}^{\infty} \oplus\ \mathcal{M}_je^{ij\theta}.$$

This decomposition is called the Fourier decomposition of $\mathcal{M}$. In general, $\mathcal{M}$ does not have the Fourier decomposition but we can get an extension $\tilde{\mathcal{M}}$ of $\mathcal{M}$ which has the Fourier decomposition :

$$\tilde{\mathcal{M}} = \sum_{j=-\infty}^{\infty} \oplus\ (\text{closure of } \mathcal{M}_j)e^{ij\theta}.$$

Proposition 3. *If $\mathcal{M}$ is an invariant subspace which contains L_a^2 and $e^{i\theta}\mathcal{M} \subseteq \mathcal{M}$, then $\mathcal{M} = \chi_E \bar{q}\mathbf{H}^2 \oplus \chi_{E^c}L^2$ where χ_E is a characteristic function in $\mathcal{L}^2$ and q is a unimodular function in $\mathbf{H}^2$. Hence $\mathcal{M} \supseteq \mathbf{H}^2$. If $\bigcap_{j=0}^{\infty} e^{ij\theta}\mathcal{M} = \{0\}$ then $\mathcal{M} = \bar{q}\mathbf{H}^2$.*

Proof. Suppose $S_0 = \mathcal{M} \ominus e^{i\theta}\mathcal{M}$, then $\mathcal{M} = (\sum_{j=0}^{\infty} \oplus S_0 e^{ij\theta}) \oplus \mathcal{M}_{-\infty}$ where $\mathcal{M}_{-\infty} = \bigcap_{j=0}^{\infty} e^{ij\theta}\mathcal{M}$, and $rS_0 \subset S_0$ because $r\mathcal{M}_j \subseteq \mathcal{M}_{j+1}$. It is well known that $\mathcal{M}_{-\infty} = \chi_G L^2$ for a characteristic function χ_F of some measurable subset in D. Put $E = G^c$ then there exists a function f in S_0 such that

$$|f| > 0 \text{ on } E \quad \text{and} \quad f = 0 \text{ on } F.$$

Since f is orthogonal to $fe^{ij\theta}$ for all $j \geq 0$. $|f|^2$ belongs to $\mathcal{L}^1 = L^1(d\sigma) = L^1([0,1), d\sigma)$ and so $|f|$ belongs to $\mathcal{L}^2$. Hence χ_E belongs to $\mathcal{L}^2$. Set

$$F(re^{i\theta}) = \begin{cases} f(re^{i\theta})/|f(re^{i\theta})| & \text{if } f \neq 0 \\ 1 & \text{if } f = 0 \end{cases}$$

, then F is a unimodular function in L^2. Since $rS_0 \subseteq S_0$, we can show that $\chi_E F$ belongs to S_0 and so $S_0 = \chi_E F\mathcal{L}^2$. Hence $\mathcal{M} \ominus \mathcal{M}_\infty = \chi_E F\mathbf{H}^2$. Since $1 \in \mathcal{M}$, $\chi_E \bar{F} \in \mathbf{H}^2$ and $q = \bar{F}$ belongs to $\mathbf{H}^2$.

Example

(I) For $0 < \beta < 1$, put

$$T_\beta = \overline{span}\{z^n \bar{z}^m \ ; \ \beta n \geq m \geq 0\}.$$

Then T_β is an invariant subspace and $T_\beta \supseteq L_a^2$. Put $T_\beta = L_a^2$ for $\beta = 0$ and $T_\beta = \mathbf{H}^2$ for $\beta = 1$. In general, $L_a^2 \subseteq T_\beta \subseteq \mathbf{H}^2$ and $T_\beta (0 \leq \beta < 1)$ has the following Fourier decomposition :

$$T_\beta = \sum_{j=0}^{\infty} \oplus (T_\beta)_j e^{ij\theta}$$

where $(T_\beta)_j = span\{r^j p_j(r^2) \ ; \ p_j$ is a polynomial of degree at most $\beta j/1 - \beta\}$. S.Janson and R.Rochberg [2] studied $H_\phi^{\mathcal{M}}$ when $\mathcal{M} = (\bar{T}_\beta)^\perp$. Then $(\bar{T}_\beta)^\perp = e^{i\theta}\mathbf{H}^2 \oplus \sum_{j=0}^{\infty} \oplus \{\mathcal{L}^2 \ominus (\bar{T}_\beta)_j\}e^{-ij\theta}$.

(II) For $k \geq 0$, put

$E^k = \overline{span}\{z^m \bar{z}^n \ ; \ m = 0, 1, \cdots, k \ ; \ n = m, m+1, \cdots\}$. $\bar{E}^k$ is an invariant subspace and $L_a^2 \subseteq \bar{E}^k \subseteq \mathbf{H}^2$. $\bar{E}^k$ has the following Fourier decomposition :

$$\bar{E}^k = \sum_{j=0}^{\infty} \oplus (\bar{E}^k)_j e^{ij\theta}$$

where $(\bar{E}^k)_j = span\{r^j, \cdots, r^{j+2k}\}$. E.Strose [9] studied $H_\phi^{\mathcal{M}}$ when $\mathcal{M} = (E^k)^\perp$. Then $(E^k)^\perp = e^{i\theta}\mathbf{H}^2 \oplus \sum_{j=0}^\infty \oplus \{\mathcal{L}^2 \ominus (E^k)_j\}e^{-ij\theta}$.

(III) Fix a polynomial p of degree k, that is, $p = \sum_{j=0}^k a_j z^j$. Put

$$Y(p) = \overline{span}\{z^n, z^m \bar{p} \ ; \ n \geq 0, \ m \geq 0\}$$

and

$$Y^k = \overline{span}\{z^\ell \bar{z}^j \ ; \ \ell \geq 0, \ 0 \leq j \leq k\}.$$

Both $Y(p)$ and Y^k are invariant subspaces and $L_a^2 \subseteq Y(p) \subseteq Y^k$, and Y^k has the following Fourier decompositon :

$$Y^k = \sum_{j=-k}^{\infty} \oplus \, (Y^k)_j e^{ij\theta}$$

where $Y_0^k = span\{1, r^2, \cdots, r^{2k}\}$ and $(Y^k)_j = r^j(Y_0^k)$ for $j \geq 0$, and $(Y^k)_{-j} = span\{r^{2\ell - j} \ ; \ j \leq \ell \leq k\}$ for $1 \leq j \leq k$. $(Y(p))_j \subseteq (Y^k)_j$ for any j but $Y(p)$ does not have a Fouriel decomposition. If $a_j \neq 0$ for $1 \leq j \leq k$, $(Y(p))_j = (Y^k)_j$ for any j and so $\tilde{Y}(p) = Y^k$. L.Peng, R.Rochberg and Z.Wu [7] and J.L.-M.Wang and Z.Wu [10] studied $H_\phi^{\mathcal{M}}$ when $\mathcal{M} = (\bar{Y}^k)^\perp$. In general, we can define $Y(g)$ for any function g in L^2. Usually, $Y(g)$ does not have the Fourier decomposition.

(IV) For a unimodular function q in $\mathbf{H}^2$, put $\mathcal{M} = \bar{q}\mathbf{H}^2$. Then $\mathcal{M}$ is an invariant subspace which contains $\mathbf{H}^2$. In general, $\bar{q}\mathbf{H}^2$ may not have the Fourier decomposition but for $q = e^{i\ell\theta}$ for some $\ell \geq 0$.

$$\mathcal{M} = \sum_{j=-\ell}^{\infty} \oplus \, \mathcal{L}^2 e^{ij\theta}.$$

There are a lot of invariant subspaces between $\mathbf{H}^2$ and $e^{-i\ell\theta}\mathbf{H}^2$ even if $\ell = 1$.

(V) For arbitrary closed subspaces S in $\mathcal{L}^2$, put $\mathcal{M} = \mathbf{H}^2 \ \oplus \ Se^{-i\theta}$. Then $\mathcal{M}$ is an invariant subspace between $\mathbf{H}^2$ and $e^{-i\theta}\mathbf{H}^2$.

§3. Kronecker's Theorem

In this section, the measure μ is an arbitrary finite positive Borel measure such that L_a^2 is closed. We will write

$$\mathcal{M}^\infty = \mathcal{M} \cap L^\infty$$

and for each positive integer ℓ

$$\mathcal{M}^{\infty,\ell} = \{\phi \in L^\infty \ ; \ \phi(z) = g(z)\prod_{j=1}^{\ell}(z-a_j)^{-1} \quad a.e.\mu \text{ on } D,$$
$$g \in \mathcal{M}^\infty \quad \text{and} \quad a_1,\cdots,a_\ell \in D\}.$$

Then $\mathcal{M}^\infty \subseteq \mathcal{M}^{\infty,1} \subseteq \mathcal{M}^{\infty,2} \subseteq \cdots$.

Kronecker (cf. [11, p210]) described finite rank Hankel operators on the Hardy space. Theorem 4 describes finite rank intermediate Hankel operators on the (weighted) Bergman space. However the situation is very different from that of Kronecker because $\mathcal{M}^\infty = \mathcal{M}^{\infty,\ell}$ may happen for some $\ell > 0$. See Corollarys 1 and 2.

Theorem 4. *Suppose $\mathcal{M}$ is an invariant subspace which contains zL_a^2, and ϕ is a function in L^∞. $H_\phi^{\mathcal{M}}$ is of finite rank $\leq \ell$ if and only if ϕ belongs to $\mathcal{M}^{\infty,\ell}$.*

Proof. Note that $\ker H_\phi^{\mathcal{M}} = \{f \in L_a^2 \ ; \ \phi f \in \mathcal{M}\}$. Since $\mathcal{M}$ is an invariant subspace, $\ker H_\phi^{\mathcal{M}}$ is also an invariant subspace. Proposition 1 implies the theorem.

Theorem 5. *Suppose $\mathcal{M}$ is an invariant subspace which contains L_a^2, and ϕ is a function in L^∞. Then the following (1) $\sim$ (4) are equivalent.*

(1) If $H_\phi^{\mathcal{M}}$ is of finite rank then $H_\phi^{\mathcal{M}} = 0$.

(2) $\mathcal{M}^\infty = \mathcal{M}^{\infty,\ell}$ for any $\ell > 0$

(3) If $g \in \mathcal{M}^\infty, a \in D$ and $(g(z)-g(a))/(z-a) \in L^\infty$, then $(g(z)-g(a))/(z-a)$ belongs to $\mathcal{M}^\infty$.

(4) If $\mathcal{M}'$ is an invariant subspace and $(\mathcal{M}')^\infty \supsetneq \mathcal{M}^\infty$, then there does not exist a nonzero polynomial b such that $b(\mathcal{M}')^\infty \subseteq \mathcal{M}^\infty$.

Proof. By Theorem 4, (1) $\Leftrightarrow$ (2) is clear. (1) $\Rightarrow$ (3). If there exists $g \in \mathcal{M}^\infty$ such that $(g-g(a))/(z-a) \in L^\infty$ does not belong to $\mathcal{M}^\infty$, put $\phi = (g-g(a))/(z-a)$, then $H_\phi^{\mathcal{M}}$ is of rank 1 and $H_\phi^{\mathcal{M}} \neq 0$. (3) $\Rightarrow$ (4). If (4) is not true, there exists ψ such that $\psi \notin \mathcal{M}^\infty$, $\psi \in (\mathcal{M}')^\infty$ and $b\psi \in \mathcal{M}^\infty$ for some polynomial : $b = \prod_{j=1}^{\ell}(z-a_j)$ and $a_j \in D$ $(1 \leq j \leq \ell < \infty)$. We may assume that $\phi = \psi\prod_{j=1}^{\ell-1}(z-a_j) \notin \mathcal{M}^\infty$ and $g = (z-a_\ell)\phi \in \mathcal{M}^\infty$. Then

$$\frac{g-g(a_\ell)}{z-a_\ell} = \phi \in L^\infty \quad \text{but} \quad \phi \notin \mathcal{M}^\infty.$$

(4) $\Rightarrow$ (1). By Theorem 4, if $H_\phi^{\mathcal{M}}$ is of finite rank $\leq \ell$, then $\phi \in \mathcal{M}^{\infty,\ell}$. If $\phi \notin \mathcal{M}^\infty$, suppose $\mathcal{M}'$ is an invariant subspace generated by ϕ and $\mathcal{M}$, then $(\mathcal{M}')^\infty \supsetneq \mathcal{M}^\infty$ but there does not exist a nonzero polynomial b such that $b(\mathcal{M}')^\infty \subseteq \mathcal{M}^\infty$. Since $\phi \in \mathcal{M}'$, this contradicts that $\phi \in \mathcal{M}^{\infty,\ell}$.

Corollary 1. *Suppose $(\mathrm{supp}\mu) \cap D$ is a uniqueness set for $\mathcal{H}ol(D)$. If H_ϕ^{big} is of finite rank then $H_\phi^{big} = 0$.*

Proof. (3) of Theorem 5 implies the corollay. In fact, if $g \in L_a^2 \cap L^\infty$ then $g(z) - g(a) \in (z-a)L_a^2$ by [6, the proof in (1) of Theorem 8]. Thus $(g(z)-g(a))/(z-a)$ belongs to $L_a^2 \cap L^\infty$.

Corollary 2. *Suppose $d\mu = rdrd\theta/\pi$. Let D_0 be an open subset of D and $\mathcal{M} = \{f \in L^2 ; f$ is analytic on $D_0\}$. Then $\mathcal{M}$ is an invariant subspace and if $H_\phi^{\mathcal{M}}$ is of finite rank then $H_\phi^{\mathcal{M}} = 0$.*

Proof. It is easy to see that $\mathcal{M}^\infty$ satisfies (3) of Theorem 5.

Corollary 3. *Suppose that if $H_\phi^{\mathcal{M}}$ is of finite rank then $H_\phi^{\mathcal{M}} = 0$. If $\mathcal{M}'$ is an invariant subspace which contains $\mathcal{M}$ properly, then the codimension of $\mathcal{M}$ in $\mathcal{M}'$ is infinite or $(\mathcal{M}')^\infty = \mathcal{M}^\infty$.*

Proof. If $\dim \mathcal{M}'/\mathcal{M} < \infty$, as in the proof of Proposition 2, then there exists a nonzero polynomial b such that $b\mathcal{M}' \subseteq \mathcal{M}$. Hence $b(\mathcal{M}')^\infty \subseteq \mathcal{M}^\infty$. If $(\mathcal{M}') \neq \mathcal{M}^\infty$, by Theorem 5, this contradicts that if $H_\phi^{\mathcal{M}}$ is of finite rank then $H_\phi^{\mathcal{M}} = 0$.

§4. General case

In this section, we assume that $d\mu = d\sigma(r)d\theta$ and $d\sigma([t,1)) > 0$ for any $t > 0$. Hence we can define the Fourier coefficients $\{\mathcal{M}_j\}_{j=-\infty}^\infty$ of $\mathcal{M}$. We assume $\mathcal{M} = \tilde{\mathcal{M}}$, that is, $\mathcal{M}$ has the Fourier deomposition.

Theorem 6. *Suppose $\mathcal{M}$ is an invariant subspace which contains zL_a^2 and $\phi = \sum_{j=-\infty}^\infty \phi_j(r)e^{ij\theta}$ is a function in L^∞. Then $H_\phi^{\mathcal{M}}$ is of finite rank $\leq \ell$ if and only if there exist complex numbers $b_0, \cdots, b_\ell$ such that $b_\ell = 1$ and for any integer n*

$$\sum_{j=0}^{\ell} b_j r^j \phi_{n-j}(r)$$

belongs to $\mathcal{M}_n$. If ℓ is the minimum number of complex numbers $b_1, \cdots, b_\ell$ such that $\sum_{j=0}^\ell b_j r^j \phi_{n-j}(r)$ belongs to $\mathcal{M}_n$ for all n, then $H_\phi^{\mathcal{M}}$ is of rank ℓ.

Proof. If $H_\phi^{\mathcal{M}}$ is of rank $\leq \ell$, by Theorem 4 there exists a polynomial $b = \sum_{j=0}^\ell b_j z^j$ such that $b\phi \in \mathcal{M}$. Then

$$\left(\sum_{j=-\infty}^{\infty} \phi_j(r)e^{ij\theta}\right)\left(\sum_{j=0}^{\ell} b_j r^j e^{ij\theta}\right) = \sum_{n=-\infty}^{\infty} \left(\sum_{j=0}^{\ell} \phi_{n-j}(r) b_j r^j\right) e^{in\theta}$$

and so $\sum_{j=0}^\ell b_j r^j \phi_{n-j}(r)$ belongs to $\mathcal{M}_n$ for any n. The converse and the second statement are clear by Theorem 4.

Corollary 4. *Let $\phi = \phi_t(r)e^{it\theta}$ for some integer t in Theorem 6. Then $H_\phi^{\mathcal{M}}$ is of finite rank $\leq \ell$ if and only if there exist complex numbers $b_0, \cdots, b_\ell$ such that $b_\ell = 1$ and for $t \leq n \leq \ell + t, b_{n-t}r^{n-t}\phi_t(r)$ belongs to $\mathcal{M}_n$.*

Proof. Since $\phi_j(r) = 0$ for $j \neq t$, if $n < t$ or $n > \ell + t$ then $\sum_{j=0}^{\ell} b_j r^j \phi_{n-j}(r) = 0$. For $t \leq n \leq \ell + t, \sum_{j=0}^{\ell} b_j r^j \phi_{n-j}(r) = b_{n-t}r^{n-t}\phi_t(r)$ and so the corollary follows.

Corollary 5. *Let $\phi = \sum_{j=1}^{\infty} a_j z^j + \sum_{j=0}^{\infty} a_{-j}\bar{z}^j$ in Theorem 6. Then $H_\phi^{\mathcal{M}}$ is of rank $\leq \ell$ if and only if there exist complex numbers $b_0, \cdots, b_\ell$ such that $b_\ell = 1$ and for any non-positive integer n $\sum_{j=0}^{\ell} b_j a_{n-j} r^{2j-n}$ belongs to $\mathcal{M}_n$ and for $0 < n < \ell$ $\sum_{j=n}^{\ell} b_j a_{n-j} r^{2j-n}$ belongs to $\mathcal{M}_n$.*

Proof. If $n \geq \ell$ and $n \neq 0$, then

$$\sum_{j=0}^{\ell} b_j r^j \phi_{n-j}(r) = \sum_{j=0}^{\ell} b_j a_{n-j} r^{j+n-j} = (\sum_{j=0}^{\ell} b_j a_{n-j}) r^n$$

and hence $\sum_{j=0}^{\ell} b_j r^j \phi_{n-j}(r)$ belongs to $\mathcal{M}_n$ because $zL_a^2 \subseteq \mathcal{M}$. Now Theorem 6 implies the corollary.

Theorem 6 does not give an exact relation between the rank of $H_\phi^{\mathcal{M}}$ and the number ℓ of complex numbers $b_0, \cdots, b_\ell$ such that $b_\ell = 1$. However we can show the following : If $H_\phi^{\mathcal{M}}$ is of rank ℓ, then there exist complex numbers $b_0, \cdots, b_\ell$ such that $b_\ell = 1$, $\sum_{j=0}^{\ell} b_j r^j \phi_{n-j}(r) \in \mathcal{M}_n$ for any n and $b = \sum_{j=0}^{\ell} b_j z^j$ has just ℓ zeros in D. That is, if $\ell = 1$ then $|b_0| < 1$.

By Theorem 6, $H_\phi^{\mathcal{M}} = 0$ if and only if $\phi_n \in \mathcal{M}_n$ for any n (that is, $\phi \in \mathcal{M}$). Moreover, $H_\phi^{\mathcal{M}}$ is of rank ≤ 1 if and only if there exist complex numbers $(b_0, b_1) \neq (0,0)$ such that $b_1 = 1$ and $b_0\phi_n + b_1 r\phi_{n-1} \in \mathcal{M}_n$ for any n.

§5. Big Hankel operator and $\mathcal{M} \subseteq \mathbf{H}^2$

In this section, we assume that $d\mu = d\sigma(r)d\theta$ and $d\sigma([t,1)) > 0$ for any $t > 0$. Hence we can define the Fourier coefficients $\{\mathcal{M}_j\}_{j=-k}^{\infty}$ of $\mathcal{M}$ and we assume $\mathcal{M} = \tilde{\mathcal{M}}$. In this case, $H_\phi^{\mathcal{M}}$ is close to H_ϕ^{big}. Recall examples in Section 2, that is, $T_\beta, \bar{E}^k, Y(p)$ and Y^k.

Corollary 6. *Suppose $\mathcal{M}$ is an invariant subspace between zL_a^2 and $\mathbf{H}^2$, and $\phi = \sum_{j=1}^{\infty} a_j z^j + \sum_{j=0}^{\infty} a_{-j}\bar{z}^j$. Then $H_\phi^{\mathcal{M}}$ is of finite rank $\leq \ell$ if and only if $a_{-n} = 0$ for $n > \ell$ and there exists complex numbers $b_0, \cdots, b_\ell$ such that $b_\ell = 1$ and $\sum_{j=n}^{\ell} b_j a_{n-j} r^{2j-n}$ belongs to $\mathcal{M}_n$ for $0 \leq n \leq \ell$ and $\sum_{j=0}^{\ell} b_j a_{n-j} r^{2j-n} = 0$ for $-\ell < n < 0$.*

Proof. Since $\mathcal{M} \subseteq \mathbf{H}^2$, by Corollary 5 $H_\phi^{\mathcal{M}}$ is of finite rank $\leq \ell$ if and only if there exists complex numbers $b_0, \cdots, b_\ell$ such that $b_\ell = 1$ and $\sum_{j=0}^{\ell} b_j a_{n-j} r^{2j-n} = 0$ for $n < 0$ and $\sum_{j=n}^{\ell} b_j a_{n-j} r^{2j-n} \in \mathcal{M}_n$ for $0 \leq n \leq \ell$. If $\sum_{j=0}^{\ell} b_j a_{n-j} r^{2j-n} = 0$ for $n < 0$, then $b_j a_{n-j} = 0$ for $0 \leq j \leq \ell$ and $n < 0$. Hence for each $j (0 \leq j \leq \ell)$, $b_j a_{-t} = 0$ if $t > j$. Thus $a_{-t} = 0$ if $t > \ell$.

Proposition 7. *Suppose $\mathcal{M}$ is an invariant subspace between zL_a^2 and $e^{-ik\theta}\mathbf{H}^2$ where $k \geq 0$, and $\phi = \sum_{j=0}^{\infty} \phi_{-j}(r) e^{-ij\theta}$ is a function in L^∞. Then $H_\phi^{\mathcal{M}}$ is of finite rank $\leq \ell$ if and only if*

$$\phi(z) = \frac{\sum_{j=-k}^{\ell} \psi_j(r) e^{ij\theta}}{\sum_{j=0}^{\ell} b_j r^j e^{ij\theta}}$$

where $\psi_n = \sum_{j=0}^{\ell} b_j r^j \phi_{n-j}$ belongs to $\mathcal{M}_n$ for $-k \leq n \leq \ell$. and $(b_0, \cdots, b_\ell) \in \mathbf{C}^\ell$.

Proof. Note that $\mathcal{M} \subseteq e^{-ik\theta}\mathbf{H}^2$ and $\phi_j(r) = 0$ for $j > 0$. If $H_\phi^{\mathcal{M}}$ is of finite rank $\leq \ell$, then by Theorem 6

$$\Big(\sum_{j=0}^{\ell} b_j r^j e^{ij\theta}\Big)\Big(\sum_{j=0}^{\infty} \phi_{-j}(r) e^{-ij\theta}\Big) = \sum_{n=-k}^{\ell} \psi_n(r) e^{in\theta}$$

and $\psi_n = \sum_{j=0}^{\ell} b_j r^j \phi_{n-j} \in \mathcal{M}_n$ for $-k \leq n \leq \ell$. The converse is also a result of Theorem 4.

Corollary 7. *Suppose $\mathcal{M}$ is an invariant subspace in Proposition 7. If $\phi = \phi_+ + \phi_- = \sum_{j=1}^{\infty} a_j z^j + \sum_{j=0}^{\infty} a_{-j} \bar{z}^j$ and $\phi_- \in L^\infty$, then $H_\phi^{\mathcal{M}}$ is of finte rank $\leq \ell$ if and only if*

$$\phi(z) = \phi_+ + \frac{\sum_{j=-k}^{\ell} \psi_j(r) e^{ij\theta}}{\sum_{j=0}^{\ell} b_j r^j e^{ij\theta}}$$

where $\psi_n = \sum_{j=0}^{\ell} b_j a_{n-j} r^{j+|n-j|}$ belongs to $\mathcal{M}_n$ for $-k \leq n \leq \ell$ and $(b_0, \cdots, b_\ell) \in \mathbf{C}^\ell$. If $(b_0, \cdots, b_\ell) = (0, \cdots, 0)$, then $\psi_n = 0$ and so $\phi = \phi_+$.

Theorem 8. *Suppose $\mathcal{M}$ is an invariant subspace between zL_a^2 and $e^{-ik\theta}\ \mathbf{H}^2$ where $k \geq 0$, and $\phi = \sum_{j=1}^{\infty} \phi_{-j}(r) e^{ij\theta}$ is a function in L^∞. Then,*

(1) If $\mathcal{M}_j \cap r^{j+1}\mathcal{L}^2 = \{0\}$ for any $j \geq 0$, then there does not exist any finite rank $H_\phi^{\mathcal{M}}$ except $H_\phi^{\mathcal{M}} = 0$.

(2) If there does not exist any finite rank $H_\phi^{\mathcal{M}}$ except $H_\phi^{\mathcal{M}} = 0$, then $\mathcal{M}_{-(k-j)} \cap r^{j+1}\mathcal{L}^\infty = \{0\}$ for any $j \geq 0$.

Proof. (1) If $H_\phi^{\mathcal{M}}$ is of finite rank ℓ, by Proposition 7

$$\psi_n = \sum_{j=n}^{\ell} b_j r^j \phi_{n-j} \in \mathcal{M}_n$$

for $0 \leq n \leq \ell$ because $\phi_{n-j}(r) = 0$ for $0 \leq j \leq n-1$. We may assume $b_\ell = 1$. As $n = \ell - 1$, $r^\ell \phi_{-1}(r) \in \mathcal{M}_{\ell-1}$. Since $\mathcal{M}_{\ell-1} \cap r^\ell \mathcal{L}^2 = \{0\}$, $\phi_{-1}(r) = 0$. As $n = \ell - 2$,

$$b_{\ell-1} r^{\ell-1} \phi_{-1}(r) + r^\ell \phi_{-2}(r) \in \mathcal{M}_{\ell-2}.$$

Since $\mathcal{M}_{\ell-2} \cap r^{\ell-1}\mathcal{L}^2 = \{0\}$ and $\phi_{-1}(r) = 0$, $\phi_{-2}(r) = 0$. we can get $\phi_{-j}(r) = 0$ for $j \leq \ell$. In Proposition 7, $\psi_n = 0$ for $0 \leq n \leq \ell$ and so $\phi \equiv 0$.

(2) If $r^{j+1}g \in \mathcal{M}_{-(k-j)} \cap r^{j+1}\mathcal{L}^\infty$, then put $\phi = ge^{-i(k+1)\theta}$. If $g \neq 0$ then $\phi \notin \mathcal{M}$ and

$$z^{j+1}\phi = r^{j+1}g\ e^{-i(k-j)\theta} \in \mathcal{M}_{-(k-j)}e^{-i(k-j)\theta}.$$

Since $\mathcal{M}$ has the Fourier decomposition, $\mathcal{M}_j e^{ij\theta} \subseteq \mathcal{M}$ and so $z^{j+1}\phi \in \mathcal{M}$. Theorem 4 gives a contradiction.

We will apply results in this section to Example in Section 2.

Example.

(I) Suppose $\mathcal{M} = T_\beta$ $(0 \leq \beta < 1)$.

(1) When $\phi = \sum_{j=1}^\infty \phi_{-j}(r)e^{-ij\theta}$ is a function in L^∞, there does not exist any finite rank $H_\phi^{\mathcal{M}}$ except $H_\phi^{\mathcal{M}} = 0$ if and only if $\beta = 0$.

(2) When $\phi = \sum_{j=0}^\infty a_j z^j + \sum_{j=1}^\infty a_{-j}\bar{z}^j$ is a function in L^∞, there does not exist any finite rank $H_\phi^{\mathcal{M}}$ except $H_\phi^{\mathcal{M}} = 0$ if and only if $\beta = 0$.

Proof. Recall that $T_\beta = \sum_{j=0}^\infty \oplus (T_\beta)_j e^{ij\theta}$ and $(T_\beta)_j = span\{r^j p_j(r^2)\ ;\ p_j$ is a polynomial of degree at most $\beta j/1-\beta\}$. (1) If $\beta = 0$ then $(T_\beta)_j \cap r^{j+1}\mathcal{L}^2 = \{0\}$ for any $j \geq 0$ and if $\beta \neq 0$ then $(T_\beta)_j \cap r^{j+1}\mathcal{L}^\infty \neq \{0\}$ for enough large j. Theorem 8 implies (1). (2) If $\beta \neq 0$, then there exists n such that $1-\beta \leq \beta(n-1)$. Hence $(T_\beta)_{n-1} \ni r^{n+1}$. Suppose $\phi = \bar{z}$ then $z^n\phi = r^{n+1}e^{i(n-1)\theta}$ and so $z^n\phi \in (T_\beta)_{n-1}e^{i(n-1)\theta} \subset T_\beta$. By Theorem 4 $H_\phi^{\mathcal{M}}$ is of rank $\leq n$ and $H_\phi^{\mathcal{M}} \neq 0$.

(II) Suppose $\mathcal{M} = \bar{E}^m$ $(0 \leq m < \infty)$.

(1) When $\phi = \sum_{j=1}^\infty \phi_{-j}(r)e^{-ij\theta}$, there does not exist any finite rank $H_\phi^{\mathcal{M}}$ except $H_\phi^{\mathcal{M}} = 0$ if and only if $m = 0$.

(2) When $\phi = \sum_{j=0}^\infty a_j z^j + \sum_{j=1}^\infty a_{-j}\bar{z}^j$ is a function in L^∞, there does not exist any finite rank $H_\phi^{\mathcal{M}}$ except $H_\phi^{\mathcal{M}} = 0$ if and only if $m = 0$ or 1.

Proof. Recall that $(\bar{E})^m = \sum_{j=0}^\infty \oplus (\bar{E}^m)_j e^{ij\theta}$ and $(\bar{E}^m)_j = span\{r^j, \cdots, r^{j+2m}\}$. (1) If $m = 0$ then $(\bar{E}^m)_j \cap r^{j+1}\mathcal{L}^2 = \{0\}$ for any $j \geq 0$ and if $m \neq 0$ then $(\bar{E}^m)_j \cap r^{j+1}\mathcal{L}^\infty \neq \{0\}$ for any $j \geq 0$. Theorem 8 implies (1). (2) If $m = 0$, by (1) there does not exist any finite rank $H_\phi^{\mathcal{M}}$ except $H_\phi^{\mathcal{M}} = 0$. If $m = 1$, then $(E^m)_n = span\{r^n, r^{n+2}\}$ for $n \geq 0$. When H_ϕ^M is of finite rank ℓ, by Corollary 6 $a_{-n} = 0$ for $n > \ell$ and if $0 \leq n \leq \ell$

$$\sum_{j=n}^{\ell} b_j a_{n-j} r^{2j-n} = cr^n + dr^{n+2}$$

for complex contants c, d. Hence for $0 \leq n \leq \ell$

$$b_j a_{n-j} = 0 \quad \text{for } n+2 \leq j \leq \ell.$$

Since $b_\ell = 1$, $a_{n-\ell} = 0$ for $0 \leq n \leq \ell$ and so $a_{-j} = 0$ for $0 \leq j \leq \ell$. When $m \geq 2$, if $\phi = \bar{z}$ then $z\phi = r^2 \in (\bar{E}^m)_0 = span\{1, r^2, \cdots, r^{2m}\}$ and $z\phi \in \bar{E}^m$ because $(\bar{E}^m)_0 \subset \bar{E}^m$. However $H_\phi^{\mathcal{M}} \neq 0$.

(III) Suppose $\mathcal{M} = Y^k$

(1) When $\phi = \sum_{j=1}^{\infty} \phi_{-j}(r)e^{-ij\theta}$, there does not exist any finite rank $H_\phi^{\mathcal{M}}$ except $H_\phi^{\mathcal{M}} = 0$ if and only if $k = 0$.

(2) When $\phi = \phi_+ + \phi_- = \sum_{j=0}^{\infty} a_j z^j + \sum_{j=1}^{\infty} a_{-j}\bar{z}^j$ and ϕ_+ are functions in L^∞, there does not exist any finite rank $H_\phi^{\mathcal{M}}$ except $H_\phi^{\mathcal{M}} = 0$ if and only if $k = 0$.

Proof. Since $H_\phi^{\mathcal{M}} = H_{\phi_-}^{\mathcal{M}}$, it is sufficient to prove (1). Recall that $Y^k = \sum_{j=-k}^{\infty} \oplus (Y^k)_j e^{ij\theta}$ where $Y_0^k = span\{1, r^2, \cdots, r^{2k}\}$ and $(Y^k)_j = r^j (Y^k)_0$ for $j \geq 0$, and $(Y^k)_{-j} = span\{r^{2\ell - j},\ j \leq \ell \leq k\}$ for $1 \leq j \leq k$. If $k = 0$ then $Y^k = L_a^2$. If $k \geq 1$, $(Y^k)_{-k} = span\{r^k\}$. (2) of Theorem 8 implies that there exists a nonzero finite rank $H_\phi^{\mathcal{M}}$.

§6. Small Hankel operator and $\mathcal{M} \supseteq \mathbf{H}^2$

In this section, we assume that $d\mu = d\sigma(r)d\theta$ and $d\sigma([t, 1)) > 0$ for any $t > 0$ Hence we can define the Fourier coefficients $\{\mathcal{M}_j\}_{j=-\infty}^{\infty}$ of $\mathcal{M}$. In this case, $H_\phi^{\mathcal{M}}$ is close to H_ϕ^{small} and far from H_ϕ^{big}. Note that if $\mathcal{M}'$ is an invariant subspace and $\mathcal{M}' \subseteq e^{i\theta}\mathbf{H}^2$ then $\mathcal{M} = (\bar{\mathcal{M}}')^\perp$ is an invariant subspace and $\mathcal{M} \supseteq e^{i\theta}\mathbf{H}^2$.

Proposition 10. *Suppose $\mathcal{M}$ is an invariant subspace which contains $e^{ik\theta}\mathbf{H}^2$ for some nonnegative integer k. If $\mathcal{M} \neq L^2$, there exists at least a nonzero finite rank $H_\phi^{\mathcal{M}}$.*

Proof. If $\bar{z}^n \in \mathcal{M}$ for all $n \geq 1$, then $z^\ell \bar{z}^n \in \mathcal{M}$ for all $\ell \geq 1$ because $z\mathcal{M} \subseteq \mathcal{M}$. Let $\mathcal{E}$ be the closed linear span of $\{z^\ell \bar{z}^n\ ;\ n \geq 1,\ \ell \geq 0\}$, then $\mathcal{E} \subseteq \mathcal{M}$ and $g\mathcal{E} \subseteq \mathcal{E}$ for arbitrary polynomial g of z and $\bar{z}$. It is well known that $\mathcal{E} = L^2$. This conrtadiction implies that there exists at least n such that $\bar{z}^n \notin \mathcal{M}$ and $n \geq 1$. If $\phi = \bar{z}^n$ then $z^{n+k}\phi \in \mathcal{M}$. Then $H_\phi^{\mathcal{M}} \neq 0$ but $H_\phi^{\mathcal{M}}$ is of finite rank $\leq n + k$ by Theorem 4.

Proposition 11. *Suppose $\mathcal{M}$ is an invariant subspace which contains $e^{ik\theta}\mathbf{H}^2$ for some nonnegative integer k. The following (1) $\sim$ (3) are valid.*

(1) If $\phi = \sum_{j=-\infty}^{\infty} \phi_j(r)e^{ij\theta}$ is a function in L^∞, then there exists a function ϕ' in L^2 such that $\phi' = \sum_{j=0}^{k-1} \phi_j(r)e^{ij\theta} + \sum_{j=1}^{\infty} \phi_{-j}(r)e^{-ij\theta}$ and $H_{\phi'}^{\mathcal{M}} = H_\phi^{\mathcal{M}}$.

(2) If $\phi = \sum_{j=k}^{\infty} \phi_j(r)e^{ij\theta}$ is a function in L^∞, then $H_\phi^{\mathcal{M}} = 0$.

(3) If $\phi = \sum_{j=-\ell}^{\infty} \phi_j(r)e^{ij\theta}$ is a function in L^∞, then $H_\phi^{\mathcal{M}}$ is of rank $\leq \ell + k < \infty$. Conversely if one of (1) or (2) is valid, then $\mathcal{M}$ contains $e^{ik\theta}\mathbf{H}^2$.

Proof. Both (1) and (2) are clear because $\mathcal{M} \supseteq e^{ik\theta}\mathbf{H}^2$. (3) is a result of Theorem 4. The converse is also clear.

We will consider Example in Section 2.

Example.

(II) Suppose $\mathcal{M} = (E^k)^{\perp}$ $(0 \leq k < \infty)$ and $\phi = \sum_{j=-\infty}^{\infty} \phi_j(r)e^{ij\theta}$ is a function in L^{∞}.

(1) $H_{\phi}^{\mathcal{M}} = 0$ if and only if

$$\int_0^1 \phi_{-j}(r) r^{j+2t} d\sigma = 0 \quad (j \geq 0,\ 0 \leq t \leq k).$$

(2) $H_{\phi}^{\mathcal{M}}$ is of rank ≤ 1 if and only if there exist complex numbers $(b_0, b_1) \neq (0,0)$ such that

$$b_0 \int_0^1 \phi_{-j}(r) r^{j+2t} d\sigma = -b_1 \int_0^1 \phi_{-j-1}(r) r^{j+2t+1} d\sigma$$

for $j \geq 0,\ 0 \leq t \leq k$.

(3) Suppose $d\sigma = rdr/2\pi$. When $\phi = \sum_{j=0}^{\infty} a_j z^j + \sum_{j=1}^{\infty} a_{-j} \bar{z}^j$, if $H_{\phi}^{\mathcal{M}}$ is of rank ≤ 1, then $H_{\phi}^{\mathcal{M}} = 0$.

Proof. From the remark in the last part of Section 4, (1) and (2) follows. (3) By (2), $H_{\phi}^{\mathcal{M}}$ is of rank ≤ 1 if and only if there exist complex numbers $(b_0, b_1) \neq (0,0)$ such that

$$b_0 a_{-j} \frac{1}{2j + 2t + 1} = -b_1 a_{-j-1} \frac{1}{2j + 2t + 3}$$

for $j \geq 0,\ 0 \leq t \leq k$. When $k \neq 0$, for each j, as $t = 0$

$$b_0 a_{-j} \frac{1}{2j + 1} = -b_1 a_{-j-1} \frac{1}{2j + 3}$$

and

$$b_0 a_{-j} \frac{1}{2j + 3} = -b_1 a_{-j-1} \frac{1}{2j + 5}.$$

This implies that $a_{-j} = a_{-j-1} = 0$ for $j \geq 0$ and so $\phi = \sum_{j=1}^{\infty} a_j z^j$. When $k = 0$, Corollary 1 implies (3)

(IV) Suppose $\mathcal{M} = \bar{q}\mathbf{H}^2$ for some unimodular function q in $\mathbf{H}^2$ and ϕ is a function in L^{∞}. $H_{\phi}^{\mathcal{M}}$ is of finite rank ℓ if and only if

$$\phi = \bar{q} \sum_{j=-\ell}^{\infty} \psi_j(r) e^{ij\theta}$$

where $\psi_{-\ell}(r) \neq 0$.

Proof. If $\phi = \bar{q} \sum_{j=-\ell}^{\infty} \psi_j(r) e^{ij\theta}$, then $z^{\ell}\phi$ belongs to $\mathcal{M}$ and so by Theorem 4 $H_{\phi}^{\mathcal{M}}$ is of finite rank $\leq \ell$. Since $\psi_{-\ell}(r) \neq 0$, $b\phi \notin \mathcal{M}$ for any polynomial b of degree $\leq \ell - 1$ and so $H_{\phi}^{\mathcal{M}}$ is of finite rank ℓ. The converse is clear.

(V) Suppose $\mathcal{M} = \mathbf{H}^2 \oplus Se^{-i\theta}$ and S is a closed subspace in $\mathcal{L}^2$. Let $\phi = \sum_{j=-\infty}^{\infty} \phi_j(r) e^{ij\theta}$ be a function in L^{∞}. By Theorems 4 and 6, $H_{\phi}^{\mathcal{M}}$ is of finite rank $\leq \ell$ if and only if $\phi_j(r) = 0$ for $j \leq -(\ell+2)$ and there exist complex numbers $b_0, \cdots, b_\ell$ such that $b_\ell = 1$,

$$\sum_{j=0}^{\ell} b_j r^j \phi_{n-j}(r) = 0 \quad \text{for } -(\ell+1) \leq n < -1$$

and

$$\sum_{j=0}^{\ell} b_j r^j \phi_{-1-j}(r) \in S.$$

§7. Restricted shift opeator and $\mathcal{M} \subseteq L_a^2$.

In this section, we assume $\mu = rdrd\theta/\pi$ for simplicity. Let $\mathcal{M}$ be an invariant subspace in L_a^2 and $\mathcal{K} = L_a^2 \ominus \mathcal{M}$. For ϕ in $L_a^\infty = L_a^2 \cap L^\infty$

$$S_\phi^\mathcal{K} f = (I - P^\mathcal{K})(\phi f) \quad (f \in \mathcal{K})$$

where $P^\mathcal{K}$ is the orthogonal projection from L_a^2 to $\mathcal{K}$. $S_z^\mathcal{K}$ is called a restricted shift operator. For any ϕ in L_a^∞ $S_\phi^\mathcal{K}$ commutes with $S_z^\mathcal{K}$. We don't know whether if the bounded linear operator T on $\mathcal{K}$ commutes with $S_z^\mathcal{K}$ then $T = S_\phi^\mathcal{K}$ for some ϕ in L_a^∞. If $TS_z^\mathcal{K} = S_z^\mathcal{K} T$ and $\phi = TP^\mathcal{K}1$ is bounded, then it is easy to see that $T = S_\phi^\mathcal{K}$ (cf. [5, p784]). In the Hardy space instead of the Bergman space, D.Sarason [8] showed that this is true without any condition and $\|T\| = \|\phi\|_\infty$.

We can define the Hankel operator $H_\phi^\mathcal{M}$ as in Introduction. However $H_\phi^\mathcal{M}$ is not an intermediate Hankel operator. It is not so difficult to see the following : When $\mathcal{K} = L_a^2 \ominus \mathcal{M}$ and ϕ in L_a^∞,

$$\|H_\phi^\mathcal{M}\| = \|S_\phi^\mathcal{K}\|.$$

This is known for the Hardy space. In fact, for f in L_a^2

$$H_\phi^\mathcal{M} f = (I - P^\mathcal{M})\phi f = P^\mathcal{K} \phi P^\mathcal{K} f$$

and so $H_\phi^\mathcal{M} f = S_\phi^\mathcal{K} P^\mathcal{K} f$ for f in L_a^2. Hence $H_\phi^\mathcal{M}$ is of finite rank n if and only if $S_\phi^\mathcal{K}$ is of finite rank n. It is easy to see that $S_\phi^\mathcal{K}$ is of finite rank $\ell \leq n$ if and only if there exists an analytic polynomial p of degree $\ell \leq n$ such that $p(\phi)$ belongs to $\mathcal{M}^\infty$. When ϕ is in L^∞, Theorems 4 and 6 are true for $H_\phi^\mathcal{M}$.

Suppose ϕ is a function in L_a^∞.

(1) $L_a^2 \supseteq \ker H_\phi^\mathcal{M} \supseteq \mathcal{M}$.

(2) When the common zero set $Z(\mathcal{M})$ of $\mathcal{M}$ in D is empty, if $H_\phi^\mathcal{M}$ is of finite rank then $H_\phi^\mathcal{M} = 0$. This is a result of (1) and Proposition 1.

(3) If $Z(\mathcal{M})$ is not empty, there exists a nonzero finite rank $H_\phi^\mathcal{M}$.

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