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BACKWARD SHIFT INVARIANT SUBSPACES IN THE BIDISC III

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ABSTRACT. In the previous paper, we give a characterization of backward shift invariant subspaces of the Hardy space in the bidisc which satisfy the doubly commuting condition $S_z S_w^* = S_w^* S_z$ for the compression operators S_z and S_w . In this paper, we give a characterization of backward shift invariant subspaces satisfying $S_z^2 S_w^* = S_w^* S_z^2$.

1. INTRODUCTION.

Let Γ^2 be the 2-dimensional unit torus. We denote by $(z, w) = (e^{i\theta}, e^{i\phi})$ the variables in $\Gamma^2 = \Gamma_z \times \Gamma_w$. Let $L^2 = L^2(\Gamma^2)$ be the usual Lebesgue space on Γ^2 with the norm $\|f\|_2 = (\int_{\Gamma^2} |f(e^{i\theta}, e^{i\phi})|^2 d\theta d\phi / (2\pi)^2)^{1/2}$. Then L^2 is a Hilbert space with the usual inner product. For $f \in L^2$, the Fourier coefficients are given by

$$\hat{f}(n, m) = \int_{\Gamma^2} f(e^{i\theta}, e^{i\phi}) e^{-in\theta} e^{-im\phi} d\theta d\phi / (2\pi)^2 = \langle f, z^n w^m \rangle.$$

Let $H^2 = H^2(\Gamma^2)$ be the Hardy space on Γ^2 , that is,

$$H^2 = \{f \in L^2; \hat{f}(n, m) = 0 \text{ if } n < 0 \text{ or } m < 0\}.$$

For $f \in H^2$, we can write f as

$$f = \sum_{i,j=0}^{\infty} \oplus a_{i,j} z^i w^j, \quad \text{where } \sum_{i,j=0}^{\infty} |a_{i,j}|^2 < \infty.$$

Let P be the orthogonal projection from L^2 onto H^2 . For a closed subspace M of L^2 , we denote by P_M the orthogonal projection from L^2 onto M . For a function $\psi \in L^\infty$, let $L_\psi f = \psi f$ for $f \in L^2$. The Toeplitz operator T_ψ is defined by $T_\psi f = P L_\psi f$ for $f \in H^2$. It is well known that $T_\psi^* = T_{\bar{\psi}}$ and $T_{z^n}^* T_w^m = T_w^m T_{z^n}^*$ for $n, m \geq 1$. A function $f \in H^2$ is called inner if $|f| = 1$ on Γ^2 almost everywhere. A closed subspace M of H^2 is called invariant if $zM \subset M$ and $wM \subset M$. In one variable

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case, an invariant subspace M of $H^2(\Gamma)$ has a form $M = qH^2(\Gamma)$, where q is inner. This is the well known Beurling theorem [B]. In two variable case, the structure of invariant subspaces of H^2 is very complicated, see [AC], [DY], [Na1], and [R].

Let M be an invariant subspace of H^2 . Then $T_z^*(H^2 \ominus M) \subset (H^2 \ominus M)$ and $T_w^*(H^2 \ominus M) \subset (H^2 \ominus M)$. A closed subspace N of H^2 is called *backward shift invariant* if $H^2 \ominus N$ is invariant. In [IY], the first author and Yang studied backward shift invariant subspaces N on which T_z^* is strictly contractive. See [CR] and [S] for studies of backward shift invariant subspaces on the unit circle Γ .

Let M be an invariant subspace of H^2 and $\psi \in L^\infty$. Let V_ψ be the operator on M defined by $V_\psi = P_M L_\psi|_M$. Then $V_z = T_z$ and $V_z^* = V_{\bar{z}}$ on M . In [M], Mandrekar proved that $V_z V_w^* = V_w^* V_z$ on M if and only if M is Beurling type, that is, $M = qH^2$ for some inner function q in H^∞ , see also [CS] and [Na2].

For $\psi \in L^\infty$, let $S_\psi = P_N L_\psi|_N$. Then we have $S_\psi^* = S_{\bar{\psi}}$ and $S_z^* = T_z^*$ on N . In the previous paper [INS], we characterized backward shift invariant subspaces N which satisfy the condition $S_z S_w^* = S_w^* S_z$ on N as follows.

Theorem A. *Let N be a backward shift invariant subspace of H^2 and $N \neq H^2$. Then $S_z S_w^* = S_w^* S_z$ on N if and only if N has one of the following forms;*

- (i) $N = H^2 \ominus q_1(z)H^2$,
- (ii) $N = H^2 \ominus q_2(w)H^2$,
- (iii) $N = (H^2 \ominus q_1(z)H^2) \cap (H^2 \ominus q_2(w)H^2)$,

where $q_1(z)$ and $q_2(w)$ are one variable inner functions.

This paper is a continuation of previous papers [IN] and [INS]. Here we are interesting in backward shift invariant subspaces N of H^2 satisfying that $S_{z^n} S_w^* = S_w^* S_{z^n}$ for given positive integers n and m . Up to now, we can not give a complete characterization of N satisfying $S_{z^n} S_w^* = S_w^* S_{z^n}$. If $S_z S_w^* = S_w^* S_z$, then trivially $S_{z^n} S_w^* = S_w^* S_{z^n}$. But the converse is not true. In this paper, we concentrated on the case $m = 1$. One reason is the work of this paper deeply concerns with the problem of the normality of the operators S_{z^n} . For many backward shift invariant subspaces N , S_{z^n} are not normal operators, see [Y]. If S_{z^n} is normal, since $S_{z^n} S_w = S_w S_{z^n}$, by the Fuglede-Putnam theorem we have $S_{z^n} S_w^* = S_w^* S_{z^n}$. So, the results obtained in this paper will be a big help for the above mentioned problem. We will discuss on this subject in the forthcoming paper.

In Section 2, we give characterizations of N satisfying $S_{z^n}S_{w^m}^* = 0$ and $S_{w^m}^*S_{z^n} = 0$, respectively. If $S_{z^n}S_{w^m}^* = 0$, then $S_{w^m}^*S_{z^n} = 0$. The converse is not true. In Section 3, we study N satisfying $S_{z^n}S_w^* = S_w^*S_{z^n}$, and give a necessary condition for $S_{z^n}S_w^* = S_w^*S_{z^n}$. In Section 4, we study N satisfying $S_{z^2}S_w^* = S_w^*S_{z^2}$. We gave a complete characterization of such N . In [INS], we gave two different type of proofs of Theorem A. One of them is used in Section 3 and the other is used in Section 4.

Let $H^2(\Gamma_z)$ and $H^2(\Gamma_w)$ be the Hardy spaces on the unit circle Γ in variables z and w , respectively. We think that $H^2(\Gamma_z) \subset H^2$ and $H^2(\Gamma_w) \subset H^2$. For a subset E of H^2 , we denote by $[E]$ the closed linear span of E . A function $b(z) = (z - \alpha)/(1 - \bar{\alpha}z)$, $|\alpha| < 1$, is called a simple Blaschke product.

$$2. S_{z^n}S_w^* = 0 \text{ OR } S_w^*S_{z^n} = 0.$$

Let n and m be positive integers. In this section, we study backward shift invariant subspaces N of H^2 satisfying $S_{z^n}S_{w^m}^* = 0$ and $S_{w^m}^*S_{z^n} = 0$, respectively.

Lemma 2.1. *Let N be a backward shift invariant subspace of H^2 . Then we have the following.*

- (i) $S_z^n = S_{z^n}$.
- (ii) $S_{w^m}S_{z^n} = S_{z^n}S_{w^m}$ and $S_{z^n}S_{w^m}^* = S_{w^m}^*S_{z^n}$.
- (iii) If $S_{z^n}S_{w^m}^*N \neq \{0\}$, then there exists $f \in N$ such that $(S_{z^n}S_{w^m}^*f)^\wedge(0, 0) \neq 0$.

Proof. All assertions are not difficult to prove. □

The following theorem says that the structure of backward shift invariant subspaces satisfying $S_{z^n}S_{w^m}^* = 0$ is simple.

Theorem 2.2. *Let N be a backward shift invariant subspace of H^2 . Then $S_{z^n}S_{w^m}^* = 0$ if and only if N satisfies one of the following conditions;*

- (i) $N \subset \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z)$.
- (ii) $N \subset \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w)$.

Proof. Suppose that $S_{z^n}S_{w^m}^* = 0$. Then

$$(2.1) \quad S_{w^m}^*N \perp S_{z^n}N.$$

Since N is backward shift invariant, if $S_{w^m}^*N = \{0\}$ then N satisfies condition (i). If $S_{z^n}N = \{0\}$, then N satisfies (ii).

Next, suppose that

$$(2.2) \quad S_{w^m}^*N \neq \{0\} \quad \text{and} \quad S_{z^n}N \neq \{0\}.$$

We shall lead a contradiction. By (2.1), $S_{w^m}^* S_{z^n}^* N \perp S_{z^n}^* S_{w^m}^* N$. By Lemma 2.1(ii), $S_{w^m}^* S_{z^n}^* N = S_{z^n}^* S_{w^m}^* N = \{0\}$. Then

$$(2.3) \quad S_{z^n}^* N \subset \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z)$$

and

$$(2.4) \quad S_{w^m}^* N \subset \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w).$$

By (2.2) and (2.3), there exists a nonnegative integer j , $0 \leq j \leq m-1$, such that

$$(2.5) \quad \{0\} \neq S_{w^j}^* S_{z^n}^* N \subset H^2(\Gamma_z).$$

By Lemma 2.1(iii), there exists $g \in N$ such that

$$(2.6) \quad (S_{w^j}^* S_{z^n}^* g)^\wedge(0,0) \neq 0.$$

Also by (2.2) and (2.4), there exist $f \in N$ and a nonnegative integer i , $0 \leq i \leq n-1$, such that

$$(2.7) \quad S_{z^i}^* S_{w^m}^* f \in H^2(\Gamma_w)$$

and

$$(2.8) \quad (S_{z^i}^* S_{w^m}^* f)^\wedge(0,0) \neq 0.$$

Then

$$\begin{aligned} 0 &= \langle S_{w^m}^* S_{z^i}^* f, S_{z^n}^* S_{w^j}^* g \rangle && \text{by (2.1)} \\ &= \langle S_{z^i}^* S_{w^m}^* f, S_{w^j}^* S_{z^n}^* g \rangle && \text{by Lemma 2.1(ii)} \\ &= (S_{z^i}^* S_{w^m}^* f)^\wedge(0,0) \overline{(S_{w^j}^* S_{z^n}^* g)^\wedge(0,0)} && \text{by (2.5) and (2.7)} \\ &\neq 0 && \text{by (2.6) and (2.8)}. \end{aligned}$$

This is a desired contradiction.

The converse is trivial. \square

Corollary 2.3. *Let N be a backward shift invariant subspace of H^2 . Then $S_{z^n}^* S_{w^m}^* = 0$ if and only if either $S_{z^n}^* = 0$ or $S_{w^m}^* = 0$. Hence if $S_{z^n}^* S_{w^m}^* = 0$, then $S_{w^m}^* S_{z^n}^* = 0$.*

Lemma 2.4. *Let M_1 and M_2 be closed subspaces of H^2 such that*

$$M_1 \subset \sum_{j=0}^m \oplus w^j H^2(\Gamma_z) \quad \text{and} \quad M_2 \subset \sum_{i=0}^n \oplus z^i H^2(\Gamma_w).$$

Then $M_1 + M_2$ is closed.

Proof. We denote by $(z^i w^j)_{M_1}$ and $(z^i w^j)_{M_2}$ the orthogonal projections of $z^i w^j$ to the spaces M_1 and M_2 , respectively. Let

$$M'_1 = M_1 \ominus \left(\left[\{(z^i w^j)_{M_1}; 0 \leq i \leq n, 0 \leq j \leq m\} \right] \right)$$

and

$$M'_2 = M_2 \ominus \left(\left[\{(z^i w^j)_{M_2}; 0 \leq i \leq n, 0 \leq j \leq m\} \right] \right).$$

Then M'_1 and M'_2 are closed subspaces of H^2 ,

$$M'_1 \subset z^{n+1} \left(\sum_{j=0}^m \oplus w^j H^2(\Gamma_z) \right), \quad M'_2 \subset w^{m+1} \left(\sum_{i=0}^n \oplus z^i H^2(\Gamma_w) \right),$$

and

$$M'_1 + M'_2 \perp \left[\{z^i w^j; 0 \leq i \leq n, 0 \leq j \leq m\} \right].$$

Since

$$z^{n+1} \left(\sum_{j=0}^m \oplus w^j H^2(\Gamma_z) \right) \perp w^{m+1} \left(\sum_{i=0}^n \oplus z^i H^2(\Gamma_w) \right),$$

$M'_1 + M'_2 = M'_1 \oplus M'_2$ is closed. Hence

$$M_1 + M_2 = M'_1 + M'_2 + \left[\{(z^i w^j)_{M_1}, (z^i w^j)_{M_2}; 0 \leq i \leq n, 0 \leq j \leq m\} \right]$$

is closed. \square

Theorem 2.5. *Let N be a backward shift invariant subspace of H^2 . Then $S_{w^m}^* S_{z^n} = 0$ if and only if*

$$(i) \quad N \ominus \left(N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \subset N \cap \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z).$$

Proof. Suppose that $S_{w^m}^* S_{z^n} = 0$. Then $S_{z^n} N \subset \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z)$. Since $S_{z^n}^* S_{w^m} = 0$, $S_{w^m} N \subset \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w)$. First, we prove the following

$$(2.9) \quad N = \left(N \cap \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z) \right) + \left(N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right).$$

Let

$$(2.10) \quad K = \left(N \cap \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z) \right) + \left(N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right).$$

By Lemma 2.4, K is closed and $N = K \oplus (N \ominus K)$. To prove (i), it is sufficient to prove $N \ominus K = \{0\}$. We have $N \ominus K \subset N \cap (S_{z^n} N)^\perp \cap (S_{w^m} N)^\perp$. Let $f \in N \ominus K$. Then $f \perp S_{z^n} N$, so that $S_{z^n}^* f \perp N$. Since

$S_{z^n}^* f \in N$, $S_{z^n}^* f = 0$. Hence $f \in \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w)$. By (2.10), $f \in K$. This shows $f = 0$, so that $N \ominus K = \{0\}$. Thus we get (2.9).

Let

$$(2.11) \quad N_1 = \left\{ f \in N \cap \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z); f \perp N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right\}.$$

Then N_1 is a closed subspace and

$$N_1 \oplus \left(N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \subset N.$$

If the equality holds in the above, (i) holds. So we assume that

$$N_1 \oplus \left(N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \subsetneq N.$$

We shall lead a contradiction. Let

$$(2.12) \quad N_2 = N \ominus \left(N_1 \oplus \left(N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \right).$$

Then $N_2 \neq \{0\}$ and $N = N_1 \oplus N_2 \oplus \left(N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right)$.

Let $g \in N_2$ be such that $g \neq 0$. We shall prove that

$$(2.13) \quad g \notin N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \quad \text{and} \quad g \notin N \cap \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z).$$

The fact $g \notin N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w)$ is trivial. Suppose that $g \in N \cap \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z)$. By (2.11), $g \in N_1$. Since $g \in N_2$, by (2.12) we have $g \perp N_1$. Hence $g = 0$. This is a contradiction. Thus we get (2.13).

Next, we shall prove that

$$(2.14) \quad S_{z^n}^* g \not\perp N \cap \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z).$$

To prove this, suppose not. Then $S_{z^n}^* g \perp N \cap \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z)$. By (2.10), $g = g_1 + g_2$, where $g_1 \in N \cap \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z)$ and $g_2 \in N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w)$. Then $S_{z^n}^* g = S_{z^n}^* g_1 \in N \cap \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z)$. Therefore $S_{z^n}^* g = 0$, so that $g \in N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w)$. This contradicts (2.13). Thus we get (2.14).

By (2.14), there exists h_0 such that $h_0 \in N \cap \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z)$ and $\langle g, S_{z^n} h_0 \rangle = \langle S_{z^n}^* g, h_0 \rangle \neq 0$. Since $S_{z^n} h_0 \in N$, by (2.12) we have $S_{z^n} h_0 = h_1 \oplus h_2 \oplus h_3$, where $h_1 \in N_1$, $h_2 \in N_2$, and $h_3 \in$

$N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w)$. Since $g \in N_2$ and $\langle g, S_{z^n} h_0 \rangle \neq 0$, we have $h_2 \neq 0$. Since $z^n h_0 \perp \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w)$,

$$P_N z^n h_0 = S_{z^n} h_0 \perp N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w).$$

Thus we get $h_3 = 0$. By (2.12), $S_{w^m}^* N_1 = \{0\}$. Hence $S_{w^m}^* S_{z^n} h_0 = S_{w^m}^* h_2$. By (2.13) and $h_2 \in N_2$, $h_2 \notin \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z)$. This implies that $S_{w^m}^* h_2 \neq 0$. Hence $S_{w^m}^* S_{z^n} \neq 0$. This contradicts our starting assumption. Thus we have (i).

To prove the converse, suppose that condition (i) holds. Then $N = \left(N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \oplus L$, where $L \subset N \cap \sum_{j=0}^{m-1} \oplus w^j H^2(\Gamma_z)$. Let $F = F_1 + F_2 \in N$, where $F_1 \in N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w)$ and $F_2 \in L$. Since $z^n F \perp N \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w)$, $S_{z^n} F \in L$. Hence $S_{w^m}^* S_{z^n} F = 0$. Thus we get $S_{w^m}^* S_{z^n} = 0$. \square

By Theorem 2.2, the structure of backward shift invariant subspaces N satisfying $S_{z^n} S_{w^m}^* = 0$ is simple. By Theorem 2.5, the structure of backward shift invariant subspaces N satisfying $S_{w^m}^* S_{z^n} = 0$ is not so simple. When $n = m = 1$, we have the following.

Theorem 2.6. *Let N be a backward shift invariant subspace of H^2 . Then $S_w^* S_z = 0$ if and only if N has one of the following forms;*

- (i) $N = H^2(\Gamma_z) \ominus q(z)H^2(\Gamma_z)$ for some inner function $q(z)$.
- (ii) $N = H^2(\Gamma_w) \ominus q(w)H^2(\Gamma_w)$ for some inner function $q(w)$.
- (iii) Either $N = H^2(\Gamma_z) + H^2(\Gamma_w)$, or $N = H^2(\Gamma_z) + (H^2(\Gamma_w) \ominus q_2(w)H^2(\Gamma_w))$, or $N = (H^2(\Gamma_z) \ominus q_1(z)H^2(\Gamma_z)) + H^2(\Gamma_w)$, where $q_1(z)$ and $q_2(w)$ are inner functions.
- (iv) $N = (H^2(\Gamma_z) \ominus q_1(z)H^2(\Gamma_z)) + (H^2(\Gamma_w) \ominus q_2(w)H^2(\Gamma_w))$, where $q_1(z), q_2(w)$ are nonconstant inner functions and $\hat{q}_1(0)\hat{q}_2(0) = 0$.

In (iii) and (iv), since $1 \in N$, we may take q_1 and q_2 as $\hat{q}_1(0) = \hat{q}_2(0) = 0$.

Proof. By Theorem 2.2, $S_z S_w^* = 0$ if and only if either (i) or (ii) holds. By Theorem 2.5, $S_w^* S_z = 0$ if and only if

$$(2.15) \quad N \ominus (N \cap H^2(\Gamma_w)) \subset N \cap H^2(\Gamma_z).$$

If either (i) or (ii) holds, by Corollary 2.3 we have $S_w^* S_z = 0$. Suppose that N satisfies either (iii) or (iv). Then clearly $1 \in N$. Since N has a special form, it is not difficult to see that

$$N \ominus (N \cap H^2(\Gamma_w)) = \{f \in N \cap H^2(\Gamma_z); \hat{f}(0) = 0\}.$$

Hence (2.15) holds.

Next, suppose that (2.15) holds. Then we have

$$(2.16) \quad N = (N \cap H^2(\Gamma_z)) + (N \cap H^2(\Gamma_w)).$$

If either $N \cap H^2(\Gamma_z) = \{0\}$ or $N \cap H^2(\Gamma_w) = \{0\}$, then $S_z S_w^* = 0$, and by Corollary 2.3, $S_z^* S_w = 0$. Hence either (i) or (ii) holds. Suppose that $N \cap H^2(\Gamma_z) \neq \{0\}$ and $N \cap H^2(\Gamma_w) \neq \{0\}$. We shall prove $1 \in N$. To prove this, suppose that $1 \notin N$. Let 1_w be the orthogonal projection of 1 to $N \cap H^2(\Gamma_w)$. Then $1_w \notin H^2(\Gamma_z)$. Since $N \cap H^2(\Gamma_z) \neq \{0\}$, there exists $f \in N \cap H^2(\Gamma_z)$ such that $\hat{f}(0) \neq 0$. Let $f_1 = f - \hat{f}(0)1_w \in N$. Then $f_1 \notin H^2(\Gamma_z)$. Let $h \in N \cap H^2(\Gamma_w)$. Since $f \in H^2(\Gamma_z)$, $f - \hat{f}(0)1_w \perp h$. Since $1 - 1_w \perp N \cap H^2(\Gamma_w)$,

$$\langle f_1, h \rangle = \langle \hat{f}(0)(1 - 1_w) + f - \hat{f}(0), h \rangle = 0.$$

Hence $f_1 \in N \ominus (N \cap H^2(\Gamma_w))$. Thus (2.15) does not hold. Therefore $1 \in N$. Since $N \cap H^2(\Gamma_z)$ and $N \cap H^2(\Gamma_w)$ are nonzero backward shift invariant subspaces, by (2.16) N has one of forms in (iii) and (iv). \square

$$3. \quad S_{z^n} S_w^* = S_w^* S_{z^n}.$$

The following is the main theorem in this section.

Theorem 3.1. *Let N be a backward shift invariant subspace of H^2 , $N \neq \{0\}$, and $N \neq H^2$. Let $M = H^2 \ominus N$ and $n \geq 2$ be a positive integer. If $S_{z^n} S_w^* = S_w^* S_{z^n}$, then one of the following conditions holds;*

- (i) $S_z S_w^* = S_w^* S_z$.
- (ii) $M \cap H^2(\Gamma_z) = q_1(z)H^2(\Gamma_z)$ for an inner function $q_1(z)$ satisfying $q_1(z) = \prod_{j=1}^k b_j(z)$, $1 \leq k \leq n$, where b_i are simple Blaschke products.

The following lemma is a generalization of [IN], and the idea of the proof is the same.

Lemma 3.2. *Let N be a backward shift invariant subspace of H^2 and $M = H^2 \ominus N$. Let n be a positive integer. Then $S_{z^n} S_w^* = S_w^* S_{z^n}$ if and only if*

$$M \ominus \left(z^n M \oplus \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \right) \subset (M \cap H^2(\Gamma_z)) \oplus wM.$$

Proof. The operators T_{z^n} and T_w^* on H^2 have the matrix forms as

$$T_{z^n} = \begin{pmatrix} * & P_M T_{z^n}|_N \\ 0 & S_{z^n} \end{pmatrix}, T_w^* = \begin{pmatrix} * & 0 \\ P_N T_w^*|_M & S_w^* \end{pmatrix} \quad \text{on } H^2 = \begin{pmatrix} M \\ \oplus \\ N \end{pmatrix}.$$

Set $A = P_M T_{z^n}|_N$ and $B = P_N T_w^*|_M$. Since $T_{z^n} T_w^* = T_w^* T_{z^n}$ on H^2 , $S_{z^n} S_w^* = S_w^* S_{z^n}$ if and only if $BA = 0$. We have $T_w^*(M \ominus wM) \subset N$. For $f \in H^2$, $T_w^* f = 0$ if and only if $f \in H^2(\Gamma_z)$. Hence

$$\begin{aligned} \ker B &= \{f \in M; T_w^* f \in M\} \\ &= \{f \in M \ominus wM; T_w^* f = 0\} \oplus wM \\ &= (M \cap H^2(\Gamma_z)) \oplus wM. \end{aligned}$$

We denote by $[\text{ran } A]$ the closed range of A . Let $A_1 = P_M T_{z^n} P_N$ on H^2 . Then $[\text{ran } A] = [\text{ran } A_1]$. Since $A_1^* = P_N T_{z^n}^* P_M$, we get

$$\begin{aligned} \ker A_1^* &= \{f \in M; T_{z^n}^* f \in M\} \oplus N \\ &= \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \oplus z^n M \oplus N. \end{aligned}$$

Hence

$$[\text{ran } A] = [\text{ran } A_1] = H^2 \ominus \ker A_1^* = M \ominus \left(z^n M \oplus \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \right).$$

Since $BA = 0$ if and only if $[\text{ran } A] \subset \ker B$, we get our assertion. \square

Proof of Theorem 3.1. Suppose that $S_{z^n} S_w^* = S_w^* S_{z^n}$. By Lemma 3.2,

$$M \ominus \left(z^n M \oplus \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \right) \subset (M \cap H^2(\Gamma_z)) \oplus wM.$$

Let

$$K_0 = M \ominus \left(z^n M \oplus \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \right).$$

Then

$$(3.1) \quad K_0 \subset (M \cap H^2(\Gamma_z)) \oplus wM$$

and

$$(3.2) \quad M \ominus z^n M = K_0 \oplus \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right).$$

Since $M = \sum_{s=0}^{\infty} \oplus z^{ns} (M \ominus z^n M)$,

$$(3.3) \quad K_0 \perp \sum_{s=0}^{\infty} \oplus z^{ns} \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right)$$

and

$$(3.4) \quad M = \left(\sum_{s=0}^{\infty} \oplus z^{ns} K_0 \right) \oplus \left(\sum_{s=0}^{\infty} \oplus z^{ns} \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \right).$$

First, suppose that $K_0 = \{0\}$. In this case, we shall show that condition (i) holds. By (3.2),

$$\sum_{i=0}^{n-1} \oplus z^i (M \ominus zM) = M \ominus z^n M = M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w).$$

Let $f \in M \ominus zM$. Then $f \in M \ominus z^n M$ and $f = \sum_{i=0}^{n-1} \oplus z^i h_i(w)$, where $h_i(w) \in H^2(\Gamma_w)$. Since $f \in M \ominus zM$,

$$z^{n-1} f = \sum_{i=0}^{n-1} \oplus z^{n-1+i} h_i(w) \in M \ominus z^n M.$$

Hence $f = h_0(w)$, so that $M \ominus zM = M \cap H^2(\Gamma_w)$. By Lemma 3.2 (for the case of $n = 1$), we get $S_z S_w^* = S_w^* S_z$.

Next, suppose that $K_0 \neq \{0\}$. The proof of this case is a little bit long, so we devide into several steps.

Step 1. In this step, we shall prove that there is a nonconstant inner function $q_1(z)$ such that

$$(3.5) \quad K_0 \subset q_1(z) H^2(\Gamma_z) \oplus wM.$$

First we prove that $K_0 \not\subset wM$. To prove this, suppose that $K_0 \subset wM$. Let $F \in K_0$. Then $F = wf$ for some $f \in M$. We shall prove that $f \in K_0$. We have

$$\begin{aligned} & \left\langle f, \left(\sum_{s=1}^{\infty} \oplus z^{ns} K_0 \right) \oplus \left(\sum_{s=0}^{\infty} \oplus z^{ns} \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \right) \right\rangle \\ &= \left\langle wf, w \left(\sum_{s=1}^{\infty} \oplus z^{ns} K_0 \oplus \left(\sum_{s=0}^{\infty} \oplus z^{ns} \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \right) \right) \right\rangle \\ &= \left\langle F, z^n w \left(\sum_{s=1}^{\infty} \oplus z^{n(s-1)} K_0 \right) \right\rangle \quad \text{by (3.3)} \\ &= 0, \end{aligned}$$

where the last equality follows from $w \sum_{s=1}^{\infty} \oplus z^{n(s-1)} K_0 \subset M$ and (3.2). Hence by (3.4), we get $f \in K_0$. Therefore for every positive integer p , we have $F = w^p f_p$ for some $f_p \in K_0$. This leads $F = 0$. This is a contradiction. Thus we get $K_0 \not\subset wM$.

Hence by (3.1), $M \cap H^2(\Gamma_z) \neq \{0\}$. By the Beurling theorem,

$$(3.6) \quad M \cap H^2(\Gamma_z) = q_1(z) H^2(\Gamma_z),$$

where $q_1(z)$ is inner. Then $q_1(z) \in M$ and

$$(3.7) \quad q_1(z) H^2(\Gamma_z) \perp wM.$$

If $q_1(z)$ is constant, we have $M = H^2$, so that $N = \{0\}$. This contradicts our assumption. Hence $q_1(z)$ is a nonconstant inner function. By (3.1) and (3.6), we get (3.5).

Step 2. In this step, we prove

$$(3.8) \quad K_0 \subset q_1(z) \left(\sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right).$$

Let $G \in K_0$. Then by (3.5), $G = q_1(z)h(z) \oplus wg$, where $h(z) \in H^2(\Gamma_z)$ and $g \in M$. Write

$$h(z) = \left(\sum_{i=0}^{n-1} \oplus a_i z^i \right) \oplus z^n h_0(z).$$

Then

$$G = q_1(z) \left(\sum_{i=0}^{n-1} \oplus a_i z^i \right) \oplus q_1(z) z^n h_0(z) \oplus wg.$$

By (3.6), $q_1(z) z^n h_0(z) \in z^n M$. Since $G \in K_0 \subset M \ominus z^n M$, we have $h_0(z) = 0$. Hence

$$(3.9) \quad G = q_1(z) \left(\sum_{i=0}^{n-1} \oplus a_i z^i \right) \oplus wg.$$

Here we prove that

$$(3.10) \quad g \in K_0.$$

Since $G = q_1(z)h(z) \oplus wg$, we have

$$\begin{aligned} \left\langle g, \sum_{s=1}^{\infty} \oplus z^{ns} K_0 \right\rangle &= \left\langle wg, w \sum_{s=1}^{\infty} \oplus z^{ns} K_0 \right\rangle \\ &= \left\langle wg, w \sum_{s=1}^{\infty} \oplus z^{ns} K_0 \right\rangle + \left\langle q_1 h, w \sum_{s=1}^{\infty} \oplus z^{ns} K_0 \right\rangle \quad \text{by (3.7)} \\ &= \left\langle G, w \sum_{s=1}^{\infty} \oplus z^{ns} K_0 \right\rangle \\ &= \left\langle G, z^n w \sum_{s=1}^{\infty} \oplus z^{n(s-1)} K_0 \right\rangle \\ &= 0 \quad \text{by (3.2)}. \end{aligned}$$

We also have

$$\begin{aligned}
& \left\langle g, \sum_{s=0}^{\infty} \oplus z^{ns} \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \right\rangle \\
&= \left\langle wg, w \left(\sum_{s=0}^{\infty} \oplus z^{ns} \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \right) \right\rangle \\
&= \left\langle G, \sum_{s=0}^{\infty} \oplus z^{ns} w \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right) \right\rangle \quad \text{by (3.7)} \\
&= 0 \quad \text{by (3.3)}.
\end{aligned}$$

Hence by (3.4), we get (3.10).

Applying (3.9) and (3.10) infinitely many times, we have

$$\begin{aligned}
G &= q_1(z) \left(\sum_{i=0}^{n-1} \oplus a_i z^i \right) \oplus w q_1(z) \left(\sum_{i=0}^{n-1} \oplus b_i z^i \right) \oplus \dots \\
&\in q_1(z) \left(\sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right).
\end{aligned}$$

Therefore we get (3.8).

Step 3. In this step, we study functions in $M \ominus zM$ and the inner function $q_1(z)$. By (3.8), there is a closed subspace L such that $K_0 = q_1(z)L$ and $L \subset \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w)$. Then by (3.2),

$$M \ominus z^n M = q_1(z)L \oplus \left(M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w) \right).$$

Since $K_0 \neq \{0\}$, $L \neq \{0\}$. We have $M \ominus z^n M = \sum_{i=0}^{n-1} \oplus z^i (M \ominus zM)$. Hence $M \ominus zM \neq \{0\}$. Let $F \in M \ominus zM$ be such that $F \neq 0$. Then

$$(3.11) \quad F = \left(q_1 \sum_{i=0}^{n-1} \oplus z^i f_i \right) \oplus \sum_{i=0}^{n-1} \oplus z^i g_i,$$

where $f_i, g_i \in H^2(\Gamma_w)$,

$$(3.12) \quad q_1 \sum_{i=0}^{n-1} \oplus z^i f_i \perp M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w),$$

and

$$(3.13) \quad \sum_{i=0}^{n-1} \oplus z^i g_i \in M \cap \sum_{i=0}^{n-1} \oplus z^i H^2(\Gamma_w).$$

Since $n \geq 2$, $zF \in M \ominus z^n M$, so that we have

$$zF = q_1 \left(\sum_{i=0}^{n-1} \oplus z^i G_{1,i} \right) + \sum_{i=0}^{n-1} \oplus z^i H_{1,i},$$

where $G_{1,i}, H_{1,i} \in H^2(\Gamma_w)$. Hence

$$(3.14) \quad q_1 \left(z \left(\sum_{i=0}^{n-1} \oplus z^i f_i \right) - \sum_{i=0}^{n-1} \oplus z^i G_{1,i} \right) = \left(\sum_{i=0}^{n-1} \oplus z^i H_{1,i} \right) - z \sum_{i=0}^{n-1} \oplus z^i g_i.$$

Here we devide into two subcases.

$$\text{Subcase 1.} \quad z \left(\sum_{i=0}^{n-1} \oplus z^i f_i(w) \right) - \sum_{i=0}^{n-1} \oplus z^i G_{1,i}(w) \neq 0.$$

Then

$$q_1(z) = \frac{\left(\sum_{i=0}^{n-1} \oplus z^i H_{1,i}(w) \right) - z \sum_{i=0}^{n-1} \oplus z^i g_i(w)}{z \left(\sum_{i=0}^{n-1} \oplus z^i f_i(w) \right) - \sum_{i=0}^{n-1} \oplus z^i G_{1,i}(w)}.$$

As proved in Step 1, $q_1(z)$ is a nonconstant inner function. Then by the above, we have

$$(3.15) \quad q_1(z) = \prod_{j=1}^k b_j(z), \quad 1 \leq k \leq n,$$

where b_j are simple Blaschke products.

$$\text{Subcase 2.} \quad z \left(\sum_{i=0}^{n-1} \oplus z^i f_i(w) \right) - \sum_{i=0}^{n-1} \oplus z^i G_{1,i}(w) \equiv 0.$$

Then by (3.14), $f_{n-1} = g_{n-1} = 0$, so that by (3.11)

$$F = \left(q_1 \sum_{i=0}^{n-2} \oplus z^i f_i \right) \oplus \sum_{i=0}^{n-2} \oplus z^i g_i.$$

Since $F \in M \ominus zM$,

$$zF = \left(q_1 \sum_{i=0}^{n-2} \oplus z^{i+1} f_i \right) \oplus \sum_{i=0}^{n-2} \oplus z^{i+1} g_i \in M \ominus z^2 M.$$

In the same way as above, either (3.15) holds or $f_{n-2} = g_{n-2} = 0$. Repeat the same argument. Then either (3.15) holds or

$$f_{n-1} = f_{n-2} = \cdots = f_1 = g_{n-1} = g_{n-2} = \cdots = g_1 = 0.$$

Step 4. If (3.15) holds, then (ii) holds. So, suppose that (3.15) does not hold. Then by (3.11) and by the above fact, $F = q_1 f_0 \oplus g_0$, by (3.12) $q_1 f_0 \perp M \cap H^2(\Gamma_w)$, and by (3.13) $g_0 \in M \cap H^2(\Gamma_w)$ for every $F \in M \ominus zM$.

If $g_0 = 0$ for every $F \in M \ominus zM$, since $q_1(z) \in M$ it follows that $M \ominus zM \subset q_1(z)H^2(\Gamma_w) \subset M$. Since $M = \sum_{i=0}^{\infty} \oplus z^i(M \ominus zM)$, we have $M = q_1(z)H^2$, so that $N = H^2 \ominus q_1(z)H^2$. By Theorem A, condition (i) holds.

So we assume that $g_0 \neq 0$ for some $F \in M \ominus zM$. We shall prove that

$$(3.16) \quad (M \ominus zM) \ominus (M \cap H^2(\Gamma_w)) \subset (M \cap H^2(\Gamma_z)) \oplus wM.$$

We may assume that $(M \ominus zM) \ominus (M \cap H^2(\Gamma_w)) \neq \{0\}$. Let $G \in (M \ominus zM) \ominus (M \cap H^2(\Gamma_w))$ be such that $G \neq 0$. Then $G = q_1(z)h_1(w) \oplus h_2(w)$, where $q_1(z)h_1(w) \perp M \cap H^2(\Gamma_w)$ and $h_2(w) \in M \cap H^2(\Gamma_w)$. Hence $h_2(w) = G - q_1(z)h_1(w) \perp M \cap H^2(\Gamma_w)$. Therefore $h_2(w) = 0$. Since $q_1(z) \in M$,

$$\begin{aligned} G = q_1(z)h_1(w) &= h_1(0)q_1(z) \oplus wq_1(z) \frac{h_1(w) - h_1(0)}{w} \\ &\in M \cap H^2(\Gamma_z) \oplus wM. \end{aligned}$$

Thus we get (3.16). By Lemma 3.2 (for $n = 1$), (i) holds. \square

4. $S_{z^2}S_w^* = S_w^*S_{z^2}$ AND $S_zS_w^* \neq S_w^*S_z$.

Let N be a backward shift invariant subspace of H^2 and let n be a positive integer. Let $M = H^2 \ominus N$. Then M is an invariant subspace. If both $S_{z^n}S_w^* = S_w^*S_{z^n}$ and $S_zS_w^* \neq S_w^*S_z$ hold, then by Theorem 3.1, $M \cap H^2(\Gamma_z) = q(z)H^2(\Gamma_z)$ for some nonconstant inner function $q(z)$.

In this section, we assume that $q_1(z)H^2 \subset M$ and $M \cap H^2(\Gamma_z) = q_1(z)H^2(\Gamma_z)$ for some nonconstant inner function $q_1(z)$. Let

$$\tilde{M} = M \ominus q_1(z)H^2 \subset M.$$

Then $H^2 \ominus q_1(z)H^2 = \tilde{M} \oplus N$ and \tilde{M} is w -invariant. The following lemma is proved in [INS, Lemma 3.2].

Lemma 4.1. *Let $f \in \tilde{M}$. Then $T_w^*f \in \tilde{M}$ if and only if $f \in w\tilde{M}$.*

We denote by P_{\perp} the orthogonal projection from H^2 onto $H^2 \ominus q_1(z)H^2$. Then we have a Toeplitz type operator Q_{z^n} on $H^2 \ominus q_1(z)H^2$ such that

$$Q_{z^n} : H^2 \ominus q_1(z)H^2 \ni f \rightarrow P_{\perp}(T_{z^n}f) \in H^2 \ominus q_1(z)H^2.$$

Since $z^n M \subset M$, $Q_{z^n} \tilde{M} \subset \tilde{M}$ and $Q_z^n = Q_{z^n}$. Then Q_{z^n} has the following matrix form;

$$Q_{z^n} = \begin{pmatrix} * & P_{\tilde{M}} T_{z^n}|_N \\ 0 & S_{z^n} \end{pmatrix} \quad \text{on} \quad H^2 \ominus q_1(z)H^2 = \begin{pmatrix} \tilde{M} \\ \oplus \\ N \end{pmatrix}.$$

Since $H^2 \ominus q_1(z)H^2$ is backward shift invariant, $T_w^*(H^2 \ominus q_1(z)H^2) \subset H^2 \ominus q_1(z)H^2$. Since $T_w^*N \subset N$, the operator T_w^* on $H^2 \ominus q_1(z)H^2$ has the following matrix form;

$$T_w^* = \begin{pmatrix} * & 0 \\ P_N T_w^*|_{\tilde{M}} & S_w^* \end{pmatrix} \quad \text{on} \quad H^2 \ominus q_1(z)H^2 = \begin{pmatrix} \tilde{M} \\ \oplus \\ N \end{pmatrix}.$$

Set

$$(4.1) \quad A = P_{\tilde{M}} T_{z^n}|_N \quad \text{and} \quad B = P_N T_w^*|_{\tilde{M}}.$$

By [INS, Lemma 3.3], $T_w^* Q_z = Q_z T_w^*$ on $H^2 \ominus q_1(z)H^2$. Hence we have the following.

Lemma 4.2. $T_w^* Q_{z^n} = Q_{z^n} T_w^*$ on $H^2 \ominus q_1(z)H^2$.

Lemma 4.3. $S_{z^n} S_w^* = S_w^* S_{z^n}$ if and only if $BA = 0$.

Proof. By Lemma 4.2, $T_w^* Q_{z^n} = Q_{z^n} T_w^*$ on $H^2 \ominus q_1(z)H^2$. Then $BA + S_w^* S_{z^n} = S_{z^n} S_w^*$. Hence $S_{z^n} S_w^* = S_w^* S_{z^n}$ if and only if $BA = 0$. \square

The following is a slight generalization of [INS, Theorem 3.5].

Theorem 4.4. *Let N be a backward shift invariant subspace of H^2 and $M = H^2 \ominus N$. Suppose that $M \cap H^2(\Gamma_z) = q_1(z)H^2(\Gamma_z)$, where $q_1(z)$ is a nonconstant inner function. Let $\tilde{M} = M \ominus q_1(z)H^2$. Then the following conditions are equivalent.*

- (i) $S_{z^n} S_w^* = S_w^* S_{z^n}$ on N .
- (ii) $\tilde{M} \ominus \{f \in \tilde{M}; T_{z^n}^* f \in \tilde{M}\} \subset w\tilde{M}$.
- (iii) $T_{z^n}^* \tilde{M} \subset \tilde{M}$.

Proof. The idea of the proof is similar to the one of [INS, Theorem 3.5]. For the sake of completeness, we give the proof.

(i) \Leftrightarrow (ii) By Lemma 4.3, condition (i) is equivalent to $BA = 0$. By (4.1) and Lemma 4.1, $\ker B = \{f \in \tilde{M}; T_w^* f \in \tilde{M}\} = w\tilde{M}$. Put $A_1 = P_{\tilde{M}} T_{z^n} P_N$ on $\tilde{M} \oplus N$. Then $[\text{ran } A] = [\text{ran } A_1]$. Since $A_1^* = P_N T_{z^n}^* P_{\tilde{M}}$, $\ker A_1^* = N \oplus \{f \in \tilde{M}; T_{z^n}^* f \in \tilde{M}\}$. Hence

$$[\text{ran } A] = [\text{ran } A_1] = (\tilde{M} \oplus N) \ominus \ker A_1^* = \tilde{M} \ominus \{f \in \tilde{M}; T_{z^n}^* f \in \tilde{M}\}.$$

Therefore $BA = 0$ if and only if $\tilde{M} \ominus \{f \in \tilde{M}; T_{z^n}^* f \in \tilde{M}\} \subset w\tilde{M}$. Thus we get (i) \Leftrightarrow (ii).

(ii) \Rightarrow (iii) Suppose that $\tilde{M} \ominus \{f \in \tilde{M}; T_{z^n}^* f \in \tilde{M}\} \subset w\tilde{M}$. Since $\{f \in \tilde{M}; T_{z^n}^* f \in \tilde{M}\}$ is closed, $\tilde{M} \ominus w\tilde{M} \subset \{f \in \tilde{M}; T_{z^n}^* f \in \tilde{M}\}$. Since $w\tilde{M} \subset \tilde{M}$, $\tilde{M} = \sum_{j=0}^{\infty} \oplus w^j(\tilde{M} \ominus w\tilde{M})$. Since $T_{z^n}^* w^j f = w^j T_{z^n}^* f$ for $f \in H^2$, we have $T_{z^n}^* \tilde{M} \subset \tilde{M}$.

(iii) \Rightarrow (ii) is trivial. \square

For $f \in H^2(\Gamma_z)$, write $f^*(z) = T_z^* f(z) = \bar{z}(f(z) - \hat{f}(0))$.

Lemma 4.5. *Let $b_i(z) = (z - \alpha_i)/(1 - \bar{\alpha}_i z)$, $|\alpha_i| < 1$, and $1 \leq i \leq n$. Then*

- (i) $T_z^* z = 1$, $T_z^* b_1 = b_1^*(z) = (1 - |\alpha_1|^2)/(1 - \bar{\alpha}_1 z)$, and $T_z^* b_1^*(z) = \bar{\alpha}_1 b_1^*(z)$.
- (ii) $T_z^*(b_1(z)b_2^*(z)) = (1 - |\alpha_2|^2)b_1^*(z) + \bar{\alpha}_2 b_1(z)b_2^*(z)$.
- (iii) $H^2(\Gamma_z) \ominus (\prod_{j=1}^k b_j(z))H^2(\Gamma_z) = \sum_{j=1}^k \oplus [b_1(z) \cdots b_{j-1}(z)b_j^*(z)]$.
- (iv) $H^2 \ominus (\prod_{j=1}^k b_j(z))H^2 = \sum_{j=1}^k \oplus [b_1(z) \cdots b_{j-1}(z)b_j^*(z)H^2(\Gamma_w)]$.

Proof. It is not difficult to prove (i).

(ii) Since

$$\begin{aligned} \bar{z}b_1(z)b_2^*(z) &= \bar{z}b_1(z)\frac{1 - |\alpha_2|^2}{1 - \bar{\alpha}_2 z} \\ &= (1 - |\alpha_2|^2)b_1(z)\left(\bar{z} + \frac{\bar{\alpha}_2}{1 - \bar{\alpha}_2 z}\right) \\ &= (1 - |\alpha_2|^2)\bar{z}b_1(z) + \bar{\alpha}_2 b_1(z)b_2^*(z), \end{aligned}$$

we get (ii).

(iii) See [Ni, p.33].

(iv) follows from (iii). \square

Corollary 4.6. *Let N be a backward shift invariant subspace of H^2 and $M = H^2 \ominus N$. Suppose that $M \cap H^2(\Gamma_z) = b_1(z)H^2(\Gamma_z)$, where $b_1(z)$ is a simple Blaschke product. Then $S_z S_w^* = S_w^* S_z$.*

Proof. Let $b_1(z) = (z - \alpha)/(1 - \bar{\alpha}z)$, $|\alpha| < 1$, and $\tilde{M} = M \ominus b_1(z)H^2$. Since $b_1(z) \in M$, $b_1(z)H^2 \subset M$. By Lemma 4.5(iv), $\tilde{M} \subset b_1^*(z)H^2(\Gamma_w)$. By Lemma 4.5(i), $T_z^*(b_1^*(z)h(w)) = \bar{\alpha}_1 b_1^*(z)h(w)$. Hence $T_z^* \tilde{M} \subset \tilde{M}$. By Theorem 4.4, $S_z S_w^* = S_w^* S_z$. \square

Corollary 4.7. *Let N be a backward shift invariant subspace of H^2 and $M = H^2 \ominus N$. Suppose that $M \cap H^2(\Gamma_z) = q_1(z)H^2(\Gamma_z)$, where $q_1(z)$ is an inner function. Let n, k be positive integers with $n \geq k + 1$. Moreover suppose that $q_1(z) = z^k b(z)$, where b is a simple Blaschke product, $b(z) = (z - \alpha)/(1 - \bar{\alpha}z)$, and $\alpha \neq 0$. If $S_{z^n} S_w^* = S_w^* S_{z^n}$, then $S_{z^k} S_w^* = S_w^* S_{z^k}$.*

Proof. Let $\tilde{M} = M \ominus q_1(z)H^2$. If $\tilde{M} = \{0\}$, then $M = q_1(z)H^2$. By Theorem A, $S_z S_w^* = S_w^* S_z$. Suppose that $\tilde{M} \neq \{0\}$. By Lemma 4.5(iv),

$$\tilde{M} \subset b^*(z)H^2(\Gamma_w) \oplus \left(\sum_{j=1}^k \oplus z^{j-1} b(z)H^2(\Gamma_w) \right).$$

Let $f \in \tilde{M}$. Then

$$f = b^*(z)h_0(w) + \sum_{j=1}^k \oplus z^{j-1} b(z)h_j(w), \quad h_j(w) \in H^2(\Gamma_w).$$

By Lemma 4.5(i),

$$\begin{aligned} T_{z^n}^* f &= T_{z^{n-k}}^* (T_{z^k}^* f) \\ &= T_{z^{n-k}}^* \left(\sum_{j=0}^k \bar{\alpha}^{(k-j)} b^*(z)h_j(w) \right) \\ &= \bar{\alpha}^{(n-k)} \sum_{j=0}^k \bar{\alpha}^{(k-j)} b^*(z)h_j(w). \end{aligned}$$

Since $S_{z^n} S_w^* = S_w^* S_{z^n}$, by Theorem 4.4 $T_{z^n}^* f \in \tilde{M}$. Since $\alpha \neq 0$,

$$\sum_{j=0}^k \bar{\alpha}^{(k-j)} b^*(z)h_j(w) \in \tilde{M}.$$

Thus $T_{z^k}^* \tilde{M} \subset \tilde{M}$. By Theorem 4.4, $S_{z^k} S_w^* = S_w^* S_{z^k}$. \square

Theorem 4.8. *Let N be a backward shift invariant subspace of H^2 and $M = H^2 \ominus N$. Suppose that $M \cap H^2(\Gamma_z) = q_1(z)H^2(\Gamma_z)$, where $q_1(z)$ is an inner function. Moreover suppose that $q_1(z) = b_1(z)b_2(z)$, where $b_i(z)$, $i = 1, 2$, are simple Blaschke products, $b_i(z) = (z - \alpha_i)/(1 - \bar{\alpha}_i z)$, and $\alpha_1 \alpha_2 \neq 0$. Let $n \geq 2$ be a positive integer. Then we have the following.*

- (i) *If $S_{z^n} S_w^* = S_w^* S_{z^n}$ and $S_{z^{n-1}} S_w^* \neq S_w^* S_{z^{n-1}}$, then $\alpha_1^n = \alpha_2^n$ and $\alpha_1 \neq \alpha_2$.*
- (ii) *If $\alpha_1^n = \alpha_2^n$ and $\alpha_1 \neq \alpha_2$, then $S_{z^n} S_w^* = S_w^* S_{z^n}$.*

Proof. Let $\tilde{M} = M \ominus q_1(z)H^2$. Suppose that $S_{z^n} S_w^* = S_w^* S_{z^n}$ and $S_{z^{n-1}} S_w^* \neq S_w^* S_{z^{n-1}}$. By Theorem 4.4, $T_{z^n}^* \tilde{M} \subset \tilde{M}$ and $T_{z^{n-1}}^* \tilde{M} \not\subset \tilde{M}$. By Lemma 4.5(iv),

$$(4.2) \quad \tilde{M} \subset b_1^*(z)H^2(\Gamma_w) \oplus b_1(z)b_2^*(z)H^2(\Gamma_w).$$

Then there exists $f_0 \in \tilde{M}$ such that $T_{z^{n-1}}^* f_0 \notin \tilde{M}$, and

$$f_0 = b_1^*(z)g_1(w) + b_1(z)b_2^*(z)g_2(w) \in b_1^*(z)H^2(\Gamma_w) \oplus b_1(z)b_2^*(z)H^2(\Gamma_w).$$

By Lemma 4.5,

$$T_{z^{n-1}}^* f_0 = b_1^* \left(\bar{\alpha}_1^{(n-1)} g_1 + (1 - |\alpha_2|^2) \left(\sum_{j=0}^{n-2} \bar{\alpha}_1^{(n-2-j)} \bar{\alpha}_2^j \right) g_2 \right) + \bar{\alpha}_2^{(n-1)} b_1 b_2^* g_2$$

and

$$T_{z^n}^* f_0 = b_1^* \left(\bar{\alpha}_1^n g_1 + (1 - |\alpha_2|^2) \left(\sum_{j=0}^{n-1} \bar{\alpha}_1^{(n-1-j)} \bar{\alpha}_2^j \right) g_2 \right) + \bar{\alpha}_2^n b_1 b_2^* g_2.$$

Since $T_{z^{n-1}}^* f_0 \notin \tilde{M}$ and $f_0 \in \tilde{M}$, $T_{z^{n-1}}^* f_0 - \bar{\alpha}_2^{n-1} f_0 \notin \tilde{M}$. Then

$$b_1^* \left((\bar{\alpha}_1^{(n-1)} - \bar{\alpha}_2^{(n-1)}) g_1 + (1 - |\alpha_2|^2) \left(\sum_{j=0}^{n-2} \bar{\alpha}_1^{(n-2-j)} \bar{\alpha}_2^j \right) g_2 \right) \notin \tilde{M}.$$

Hence

$$\left(\sum_{j=0}^{n-2} \bar{\alpha}_1^{(n-2-j)} \bar{\alpha}_2^j \right) b_1^* \left((\bar{\alpha}_1 - \bar{\alpha}_2) g_1 + (1 - |\alpha_2|^2) g_2 \right) \notin \tilde{M}.$$

Since $0 \in \tilde{M}$, $\sum_{j=0}^{n-2} \bar{\alpha}_1^{(n-2-j)} \bar{\alpha}_2^j \neq 0$, so that

$$(4.3) \quad b_1^* \left((\bar{\alpha}_1 - \bar{\alpha}_2) g_1 + (1 - |\alpha_2|^2) g_2 \right) \notin \tilde{M}.$$

Since $T_{z^n}^* f_0 \in \tilde{M}$, $T_{z^n}^* f_0 - \bar{\alpha}_2^n f_0 \in \tilde{M}$. Then

$$b_1^* \left((\bar{\alpha}_1^n - \bar{\alpha}_2^n) g_1 + (1 - |\alpha_2|^2) \left(\sum_{j=0}^{n-1} \bar{\alpha}_1^{(n-1-j)} \bar{\alpha}_2^j \right) g_2 \right) \in \tilde{M}.$$

Hence

$$(4.4) \quad \left(\sum_{j=0}^{n-1} \bar{\alpha}_1^{(n-1-j)} \bar{\alpha}_2^j \right) b_1^* \left((\bar{\alpha}_1 - \bar{\alpha}_2) g_1 + (1 - |\alpha_2|^2) g_2 \right) \in \tilde{M}.$$

Now we prove (i). Suppose that $\alpha_1 = \alpha_2$. Then $\alpha_1 = \alpha_2 \neq 0$, so that $\sum_{j=0}^{n-1} \bar{\alpha}_1^{(n-1-j)} \bar{\alpha}_2^j \neq 0$. By (4.3) and (4.4), $b_1^* g_2 \notin \tilde{M}$ and $b_1^* g_2 \in \tilde{M}$. This is a contradiction. Hence $\alpha_1 \neq \alpha_2$.

Suppose that $\alpha_1^n \neq \alpha_2^n$. Then $\sum_{j=0}^{n-1} \bar{\alpha}_1^{(n-1-j)} \bar{\alpha}_2^j \neq 0$. By (4.4),

$$b_1^* \left((\bar{\alpha}_1 - \bar{\alpha}_2) g_1 + (1 - |\alpha_2|^2) g_2 \right) \in \tilde{M}.$$

This contradicts (4.3), so that $\alpha_1^n = \alpha_2^n$. Thus we get (i).

(ii) Suppose that $\alpha_1^n = \alpha_2^n$ and $\alpha_1 \neq \alpha_2$. Then $\sum_{j=0}^{n-1} \bar{\alpha}_1^{(n-1-j)} \bar{\alpha}_2^j = 0$. Let $f \in \tilde{M}$. Then by (4.2), $f = b_1^*(z) h_1(w) + b_1(z) b_2^*(z) h_2(w)$. Similarly,

we have

$$T_{z^n}^* f - \bar{\alpha}_2^n f = \left(\sum_{j=0}^{n-1} \bar{\alpha}_1^{(n-1-j)} \bar{\alpha}_2^j \right) b_1^* \left((\bar{\alpha}_1 - \bar{\alpha}_2) h_1 + (1 - |\alpha_2|^2) h_2 \right).$$

Hence $T_{z^n}^* f = \bar{\alpha}_2^n f \in \tilde{M}$, so that we get $T_{z^n}^* \tilde{M} \subset \tilde{M}$. By Theorem 4.4, $S_{z^n} S_w^* = S_w^* S_{z^n}$. \square

Corollary 4.9. *Let N be a backward shift invariant subspace of H^2 and $M = H^2 \ominus N$. Suppose that $M \cap H^2(\Gamma_z) = q_1(z) H^2(\Gamma_z)$, where $q_1(z)$ is an inner function. Moreover suppose that $q_1(z) = b_1(z) b_2(z)$, where $b_i(z)$, $i = 1, 2$, are simple Blaschke products, $b_i(z) = (z - \alpha_i)/(1 - \bar{\alpha}_i z)$, and $\alpha_1 \alpha_2 \neq 0$. Then we have the following.*

- (i) *If $S_{z^2} S_w^* = S_w^* S_{z^2}$ and $S_z S_w^* \neq S_w^* S_z$, then $\alpha_1 + \alpha_2 = 0$.*
- (ii) *If $\alpha_1 + \alpha_2 = 0$, then $S_{z^2} S_w^* = S_w^* S_{z^2}$.*

The following is the main theorem in this section.

Theorem 4.10. *Let N be a backward shift invariant subspace of H^2 , $N \neq \{0\}$, and $N \neq H^2$. Then $S_{z^2} S_w^* = S_w^* S_{z^2}$ if and only if one of the following conditions holds.*

- (i) $S_z S_w^* = S_w^* S_z$.
- (ii) $S_{z^2} S_w^* = 0$.
- (iii) *There exist two simple Blaschke products $b_1(z)$ and $b_2(z)$, $b_i(z) = (z - \alpha_i)/(1 - \bar{\alpha}_i z)$, $0 < |\alpha_i| < 1$, such that $N \subset H^2 \ominus b_1(z) b_2(z) H^2$ and $\alpha_1 + \alpha_2 = 0$.*

A backward shift invariant subspace N satisfying condition (i) is given by Theorem A. Also N satisfying condition (ii) is given by Theorem 2.2.

Proof of Theorem 4.10. Suppose that $S_{z^2} S_w^* = S_w^* S_{z^2}$. Moreover suppose that $S_z S_w^* \neq S_w^* S_z$. By Theorem 3.1, $M \cap H^2(\Gamma_z) = q_1(z) H^2(\Gamma_z)$ for an inner function $q_1(z)$ such that either $q_1(z) = b_1(z)$ or $q_1(z) = b_1(z) b_2(z)$, where $b_i(z) = (z - \alpha_i)/(1 - \bar{\alpha}_i z)$, $|\alpha_i| < 1$. If $q_1(z) = b_1(z)$, by Corollary 4.6, (i) holds.

Suppose that $q_1(z) = b_1(z) b_2(z)$. Moreover suppose that $\alpha_1 = \alpha_2 = 0$. Then $q_1(z) = z^2$. Hence $z^2 H^2 \subset M$, so that $N \subset H^2(\Gamma_w) \oplus z H^2(\Gamma_w)$. Then by Theorem 2.2, $S_{z^2} S_w^* = 0$. Thus (ii) holds.

Suppose that $\alpha_1 \neq 0$ and $\alpha_2 = 0$. Then $q_1(z) = z b_1(z)$. By Corollary 4.7, (i) holds.

Suppose that $\alpha_1 \neq 0$ and $\alpha_2 \neq 0$. Then by Corollary 4.9(i), we get $\alpha_1 + \alpha_2 = 0$. Hence (iii) holds.

Next, we prove the converse assertion. Suppose that one of conditions (i), (ii), and (iii) holds. If (i) holds, then trivially $S_{z^2}S_w^* = S_w^*S_{z^2}$. If (ii) holds, by Corollary 2.3 we have $S_{z^2}S_w^* = S_w^*S_{z^2}$.

Suppose that (iii) holds. Then $b_1(z)b_2(z)H^2(\Gamma_z) \subset M$. Hence $M \cap H^2(\Gamma_z)$ equals to either $b_1(z)H^2(\Gamma_z)$, or $b_2(z)H^2(\Gamma_z)$, or $b_1(z)b_2(z)H^2(\Gamma_z)$. By Corollary 4.6, $S_zS_w^* = S_w^*S_z$ for the first two cases. Hence $S_{z^2}S_w^* = S_w^*S_{z^2}$. For the last case, by Corollary 4.9(ii), $S_{z^2}S_w^* = S_w^*S_{z^2}$. \square

Example 4.11. We give an example of a backward shift invariant subspace N of H^2 satisfying $S_{z^2}S_w^* = S_w^*S_{z^2}$, $S_zS_w^* \neq S_w^*S_z$, and $S_{z^2}S_w^* \neq 0$. Let $q_1(z) = b_1(z)b_2(z)$, where $b_i(z)$, $i = 1, 2$, are $b_i(z) = (z - \alpha_i)/(1 - \bar{\alpha}_iz)$, $\alpha_1 + \alpha_2 = 0$, and $\alpha_1 \neq 0$. Let $q_2(w)$ be a non-constant inner function. Let $M = q_1(z)H^2 \oplus b_1(z)b_2^*(z)q_2(w)H^2(\Gamma_w)$. Then M is an invariant subspace and $M \cap H^2(\Gamma_z) = q_1(z)H^2(\Gamma_z)$. Let $N = H^2 \ominus M$. By Theorem 4.10, $S_{z^2}S_w^* = S_w^*S_{z^2}$. We have $\tilde{M} = M \ominus q_1(z)H^2 = b_1(z)b_2^*(z)q_2(w)H^2(\Gamma_w)$. Since

$$T_z^*b_1(z)b_2^*(z)q_2(w) = (1 - |\alpha_1|^2)b_1^*(z)q_2(w) + \bar{\alpha}_1b_1(z)b_2^*(z)q_2(w),$$

$T_z^*b_1(z)b_2^*(z)q_2(w) \notin \tilde{M}$. By Theorem 4.4, $S_zS_w^* \neq S_w^*S_z$. By Theorem 2.2, $S_{z^2}S_w^* \neq 0$.

We leave the following problem for the reader.

Problem 4.12. Characterize backward invariant subspaces N of H^2 satisfying $S_{z^n}S_w^* = S_w^*S_{z^n}$ for $n \geq 3$.

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