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POLYNOMIALLY BOUNDED OPERATORS AND EXT GROUPS

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Abstract. In this paper, we consider the Ext functor in the category of Hilbert modules over the disk algebra. We characterize the group $\mathrm{Ext}_{A(D)}(K,H)$ as a quotient of operators and explicitly calculate $\mathrm{Ext}_{A(D)}(K,H^2)$, where K is a weighted Hardy space. We then use our results to give a simple proof of a result due to Bourgain.

1. Introduction

In 1974, Foias and Williams studied the class of 2×2 operator matrices of the form below, [5]. Although their paper was never published, the main results appear in [3]. Foias and Williams conjectured that an operator of the form

$$R_f \quad = \quad \begin{pmatrix} S^* & \Gamma_f \\ 0 & S \end{pmatrix},$$

where S is the forward shift on ℓ^2 and Γ_f is the Hankel matrix with symbol f, is a counterexample to Halmos' famous problem: *Is every polynomially bounded operator similar to a contraction?*

What Foias and Williams proved was that R_f is similar to a contraction if and only if there is a bounded solution to the commutator equation $\Gamma_f = S^*X - XS$. This means that R_f is similar to a contraction if and only if R_f is similar to $S^*\oplus S$ via a similarity of the form $\begin{pmatrix} I & X \\ 0 & I \end{pmatrix}$. By solving the commutator equation above, one sees that all solutions have the form $X = \Gamma_g - \Gamma_f DS^*$, where $g\in H^2$ and D is the diagonal matrix $diag\,(i+1)_{i\geq 0}$. Paulsen observed that if X is a solution to the commutator equation, then $-X^t$ is a solution as well. Hence

$$Y = \frac{X-X^t}{2} = \left(\frac{(i-j)}{2}\hat{f}(i+j-1)\right)_{i,j\geq 0}$$

is a bounded solution. Here $\hat{f}(n)$ is the n^{th} Fourier coefficient of f and $\hat{f}(-1)=0$. It follows that R_f is similar to a contraction if and only if the matrix Y is bounded on ℓ^2.

Several other people have studied this operator including Peller who, in [6], proved that R_f is power bounded if and only if f' is in the Bloch class. He also

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showed that if f' is BMOA, then R_f is polynomially bounded. Bourgain showed in [1] that if f' is BMOA, then R_f is similar to a contraction.

An operator T is polynomially bounded on H if and only if the map $p \mapsto p(T)$ defined on polynomials extends to a representation of the disk algebra, $\mathbf{A(D)}$, on H. In terms of Hilbert modules, this means that the map $(p, h) \mapsto p(T)h$ extends to a Hilbert $\mathbf{A(D)}$-module action on H. The first systematic study of Hilbert modules was done by Douglas and Paulsen in [4]. Carlson and Clark were the first to study the Ext functor in this category [2],[3].

In this paper we give a concrete characterization of $\mathrm{Ext}_{\mathcal{A}}(K, H)$ as a quotient of operators and use this together with a result from [2] to calculate the groups $\mathrm{Ext}_{A(D)}(K, H^2)$ for a large class of Hilbert modules K. We then show how these results can be used to give an alternative proof of Bourgain's result mentioned above.

2. Homological preliminaries

A Hilbert module H over a function algebra $\mathcal{A}$ is a Hilbert space together with a bounded, unital homomorphism $\pi : \mathcal{A} \to \mathcal{L}(H)$. Such a map is called a representation of the algebra $\mathcal{A}$ on H. Given a representation π, one defines the module action on H by $a \cdot h = \pi(a)h$. It is easy to see that every Hilbert module action arises this way. In fact, if $\rho : \mathcal{A} \times H \to H$ defines a bounded module action on H then $\pi(a)h \equiv \rho(a, h)$ defines a representation of $\mathcal{A}$ on H.

Given two Hilbert $\mathcal{A}$-modules, (H, π_1) and (K, π_2), an operator $T \in \mathcal{L}(H, K)$ is called a Hilbert module map if $T\pi_1(a) = \pi_2(a)T$ for all $a \in \mathcal{A}$. $\mathrm{Ext}_{\mathcal{A}}(K, H)$ is defined to be the collection of equivalence classes of short exact sequences of the form

$$0 \to H \xrightarrow{\alpha} J \xrightarrow{\beta} K \to 0. \tag{1}$$

Here J is a Hilbert $\mathcal{A}$-module, α and β are Hilbert module maps and exactness means that α is 1-1, β is onto and the range of α is equal to the kernel of β. We call two such sequences equivalent if there exists a Hilbert module map between the two middle modules such that the following diagram commutes:

$$\begin{array}{ccccccccc} 0 & \to & H & \xrightarrow{\alpha} & J & \xrightarrow{\beta} & K & \to & 0 \\ & & \| & & \downarrow & & \| & & \\ 0 & \to & H & \xrightarrow{\alpha'} & J' & \xrightarrow{\beta'} & K & \to & 0 \end{array}$$

In this category, every short exact sequence is equivalent to one of the form

$$0 \to H \xrightarrow{\iota} H \oplus K \xrightarrow{P} K \to 0.$$

Here the middle module is the Hilbert space direct sum (with an appropriately defined module action), ι is the isometric inclusion and P is the orthogonal projection onto K. To see this fact, note from (1) we have $\alpha(H) = \mathrm{kernel}(\beta)$ so that $\alpha(H)$ is closed in J. As a Hilbert space then, $J = \alpha(H) \oplus \alpha(H)^{\perp}$. Since the restriction of β to $\alpha(H)^{\perp}$ maps 1-1 and onto K, β has a right inverse T. Now define $S \in \mathcal{L}(H \oplus K, J)$ by $S(h + k) = \alpha(h) + T(k)$. If π is the representation of $\mathcal{A}$ on J, then $\tilde{\pi}(a) \equiv S^{-1}\pi(a)S$ defines a representation of $\mathcal{A}$ on $H \oplus K$ such that the following diagram commutes:

$$\begin{array}{ccccccccc} 0 & \to & H & \stackrel{\iota}{\to} & H\oplus K & \stackrel{P}{\to} & K & \to & 0 \\ & & \| & & \downarrow S & & \| & & \\ 0 & \to & H & \stackrel{\alpha}{\longrightarrow} & J & \stackrel{\beta}{\longrightarrow} & K & \to & 0 \end{array}$$

If the sequence $0 \to H \stackrel{\iota}{\to} H \oplus K \stackrel{P}{\to} K \to 0$ is exact and π is the representation on $H \oplus K$, then for each $a \in \mathcal{A}$ we get the decomposition

$$\pi(a) \quad = \quad \begin{pmatrix} \pi_1(a) & \delta(a) \\ 0 & \pi_2(a) \end{pmatrix}$$

where π_1, π_2 are the representations on H and K, respectively, and $\delta : \mathcal{A} \to \mathcal{L}(K, H)$ is a derivation. A derivation δ is called *inner* if there is an operator X in $\mathcal{L}(K, H)$ such that $\delta(a) = \pi_1(a)X - X\pi_2(a)$, $a \in \mathcal{A}$. It is easy to see that the derivation δ is inner if and only if the sequence above is equivalent to the trivial sequence (i.e., the sequence where the module action on the direct sum is $\pi_1 \oplus \pi_2$). By identifying the representation with the derivation one gets the usual Hochschild characterization of $\mathrm{Ext}_{\mathcal{A}}(H, K)$ as derivations modulo inner ones.

3. Ext over the disk algebra

Recall that an operator T on a Hilbert space H is polynomially bounded if and only if $p \mapsto p(T)$ extends to a representation of the disk algebra, $\mathbf{A(D)}$, on H. On the other hand, given a representation $\pi : \mathbf{A(D)} \to \mathcal{L}(H)$, the operator $T = \pi(z)$ is polynomially bounded, where z is the function $z \mapsto z$. Note that $\pi(p) = p(T)$ for all polynomials p. Because of this correspondence we will write (H, T) for the Hilbert module H with multiplication by z determined by the operator T.

Let (H, T_0) and (K, T_1) be two Hilbert $\mathbf{A(D)}$-modules. A derivation $\delta : \mathbf{A(D)} \to \mathcal{L}(K, H)$ is uniquely determined by the operator $X = \delta(z)$ which, in turn, uniquely determines multiplication by z on $H \oplus K$. It is not hard to see that δ is inner exactly when there is a $Y \in \mathcal{L}(K, H)$ such that $X = T_0Y - YT_1$.

Let $\mathrm{PB}(K, H)$ denote the set of all $X \in \mathcal{L}(K, H)$ such that the 2×2 operator matrix

$$\begin{pmatrix} T_0 & X \\ 0 & T_1 \end{pmatrix}$$

is bounded on $\mathcal{L}(H \oplus K)$, and let $\triangle(K, H)$ be the set of all commutators T_0Y-YT$_1$ as Y ranges over $\mathcal{L}(K, H)$. It follows that $\mathrm{Ext}_{A(D)}(K, H^2)$ is isomorphic to the quotient $\mathrm{PB}(K, H)/\triangle(K, H)$.

4. $\mathrm{Ext}_{A(D)}(K, H^2)$

The Hardy space, H^2, is the Hilbert space of analytic functions on the disk satisfying

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

We will frequently identify $f \in H^2$ with its boundary values on the circle $\mathbf{T}$. P_+ will denote the orthogonal projection of $L^2(\mathbf{T})$ onto H^2 and S will denote the forward shift on H^2. That is, $Sf(z) = zf(z), f \in H^2$. The operator S is contractive on H^2 so, by von Neumann's inequality, (H^2, S) is a Hilbert $\mathbf{A(D)}$-module and the action is just pointwise multiplication.

Recall, for $k \in K$ the rank one operator $1 \otimes k \in \mathcal{L}(K, H^2)$ is defined by $(1 \otimes k)f = \langle f, k\rangle_K e_0$, where e_0 is the constant function 1.

The proof of the following theorem appears in [2] and allows one to calculate the groups $\mathrm{Ext}_{A(D)}(K, H^2)$ for a large class of Hilbert modules K. A special case of the theorem appeared in [5].

Theorem 1. *Let T be a polynomially bounded operator on K. For X in $\mathcal{L}(K, H^2)$, let*

$$R(X) \quad = \quad \begin{pmatrix} S & X \\ 0 & T \end{pmatrix}.$$

The following are equivalent:
1) *$R(X)$ is power bounded on $H^2 \oplus K$.*
2) *$R(X)$ is polynomially bounded on $H^2 \oplus K$.*
3) *$\exists\, k \in K$ and $Y \in \mathcal{L}(K, H^2)$ such that*
   i) *$X = 1 \otimes k + SY - YT$, and*
   ii) *For all $f \in K$, $\sum_{n=0}^{\infty} |\langle T^n f, k\rangle|^2 < \infty$.*

Remarks. (a) The first condition in 3) says that $R(X)$ is similar to $R(1 \otimes k)$ via the similarity $\begin{pmatrix} I & Y \\ 0 & I \end{pmatrix}$. Condition ii) is precisely the condition that $R(1 \otimes k)$ is power bounded.

(b) This theorem tells us that the equivalence class of the operator X in $\mathrm{Ext}_{A(D)}(K, H^2)$ is determined by a rank one operator of the form $1 \otimes k$ for some $k \in K$.

(c) The second condition in 3) is equivalent to the following: There exists $W \in \mathcal{L}(H^2, K)$ such that $WS = T^*W$ and $W(1) = k$. To see this note that if W intertwines S and T^* and sends 1 to k, then $W(e_n) = T^{*n}k$. So for $f \in K$, $\|W^* f\|^2 = \sum_{n=0}^{\infty} |\langle f, We_n\rangle_K|^2 = \sum_{n=0}^{\infty} |\langle T^n f, k\rangle_K|^2$.

(d) By remark (c), if we replace T by T^* in the theorem, then $R(1 \otimes k)$ is polynomially bounded if and only if $p \mapsto p(T)k$ extends to a bounded operator from H^2 into K. So if K is a functional Hilbert space such that $Tf(z) \equiv zf(z)$ is polynomially bounded, then the theorem gives us an alternative criterion for a function $k \in K$ to be an analytic multiplier of H^2 into K.

Recall that an analytic reproducing kernel Hilbert space on the disk is a Hilbert space H of analytic functions on the disk such that for each $|w| < 1$ the functional $f \mapsto f(w)$ is bounded on H. By the Riesz Representation Theorem there exist functions $k_w \in H$ such that $f(w) = \langle f, k_w\rangle_H$ for all w in the disk. The function $K(z, w) = k_w(z)$ is called the kernel function for H and we will write $H(K)$ instead of H since the kernel uniquely determines the Hilbert space H.

Corollary 1. *Let $H(K)$ be an analytic reproducing kernel Hilbert space on the disk such that $Tf(z) \equiv zf(z)$ is polynomially bounded on $H(K)$. Let $\overline{H(K)}$ denote the Hilbert module $(H(K), T^*)$. Then $\mathrm{Ext}_{A(D)}(\overline{H(K)}, H^2)$ can be identified with $\mathcal{M}(H^2, H(K))$, the set of pointwise multipliers from H^2 into $H(K)$.*

Proof. Suppose $1 \otimes g = SY - YT^*$ for some bounded Y. Multiplying on the left by S^* yields $Y = S^*YT^*$. So $\forall |w| < 1$, $0 = (Y - S^*YT^*)k_w = (1 - \overline{w}S^*)Yk_w$. Therefore, $Yk_w = 0 \ \ \forall |w| < 1$. Since the kernel functions k_w span $H(K)$, $Y = 0$. It follows from remark (c) above that $\mathrm{Ext}_{A(D)}(\overline{H(K)}, H^2)$ can be identified with the space of functions $g \in H^2(\beta)$ such that $p \mapsto p(T)g$ extends to a bounded operator from H^2 into $H^2(\beta)$. It is easy to show, using the Closed Graph Theorem together with the fact that the evaluation functionals are continuous on both H^2 and $H(K)$, that $g \in \mathcal{M}(H^2, H^2(\beta))$. □

Let $\{\beta_n\}$ be a sequence of positive numbers with $\beta_0 = 1$ and such that $\sup_{n\geq 0} \beta_n/\beta_{n+1} < \infty$. Then $H^2(\beta)$ is defined to be the Hilbert space of analytic functions $f(z) = \sum_{n=0}^{\infty} a_n z^n$ such that

$$\|f\|^2 \equiv \sum_{n=0}^{\infty} \frac{|a_n|^2}{\beta_n} < \infty.$$

It is well known, [7], that $Tf(z) = zf(z)$ is bounded on $H^2(\beta)$ and unitarily equivalent to the weighted shift on H^2 with weight sequence $\{\sqrt{\beta_n/\beta_{n+1}}\}$. Throughout, we will assume that T is a contraction so that $(H^2(\beta), T)$ is a Hilbert $\mathbf{A}(\mathbf{D})$-module.

We will use the following notation in the proposition below. For $g \in H^2$, Γ_g will denote the Hankel matrix with symbol g. That is

$$\Gamma_g = (\hat{g}(i+j))_{i,j\geq 0}\,,$$

where $\hat{g}(n)$ are the Fourier coefficients of g.

For $\varphi \in L^\infty(T)$, let T_φ denote the Toeplitz matrix

$$T_\varphi = (\hat{\varphi}(i-j))_{i,j\geq 0}\,.$$

Finally, D_β will denote the diagonal matrix, $diag\left(\sqrt{\beta_n}\right)_{n\geq 0}$.

Proposition 1. *For g in $H^2(\beta)$, define g_1 in H^2 by $\hat{g}_1(n) = \hat{g}(n)/\beta_n$. Let*

$$R(1\otimes g) \quad = \quad \begin{pmatrix} S & 1\otimes g \\ 0 & T \end{pmatrix}.$$

(1) *$R(1\otimes g)$ is polynomially bounded on $H^2 \oplus H^2(\beta)$ if and only if the weighted Hankel matrix $D_\beta\, \Gamma_{g_1}$ is bounded on ℓ^2.*

(2) *There is an operator Y in $\mathcal{L}(H^2(\beta), H^2)$ such that $1\otimes g = SY - YT$ if and only if $\exists\, \varphi \in L^\infty(\mathbf{T})$ satisfying*

a) *$P_+(\overline{e^{i\theta}\varphi(e^{i\theta})}) = -g_1$, and*

b) *The weighted Toeplitz matrix $T_\varphi\, D_\beta$ is bounded on ℓ^2.*

Proof. By remark (c), the matrix $R(1\otimes g)$ is polynomially bounded if and only if the operator $We_j = T^{*j}g$ extends to a bounded operator from H^2 into $H^2(\beta)$. One checks that the matrix for this operator with respect to the usual orthonormal bases, $\{e_n\}_{n\geq 0}$ for H^2 and $\{\sqrt{\beta_n} z^n\}_{n\geq 0}$ for $H^2(\beta)$, is the weighted Hankel matrix above. For the proof of (2), suppose $1\otimes g = SY - YT$ for some $Y \in \mathcal{L}(H^2(\beta), H^2)$. Multiplying on the left by S^*, we see that $Y = S^*YT$. It follows that the matrix $(\langle Yz^j, e_i\rangle_2)_{i,j\geq 0}$ is Toeplitz. To see that the matrix is bounded, note that T is a contraction so that ${D_\beta}^{-1}$ is bounded. Hence ${D_\beta}^{-1}Y$ is bounded. But this is the Toeplitz matrix above. From the commutator equation one has $\hat{g}_1(n) = -\langle Y^*e_0, z^{n+1}\rangle_\beta$. □

Corollary 2. $\mathrm{Ext}_{A(D)}(H^2, H^2) = (0)$.

Proof. By setting $\beta_n = 1$, one sees that $R(1\otimes g)$ is polynomially bounded if and only if the Hankel matrix Γ_g is bounded on ℓ^2. By Nehari's theorem, this happens if and only if $g = P_+\psi$ for some $\psi \in L^\infty(\mathbf{T})$. □

Corollary 3. *If $\beta_n \longrightarrow +\infty$, then we may identify* $\mathrm{Ext}_{A(D)}(H^2(\beta), H^2)$ *as the vector space of functions $g \in H^2(\beta)$ such that the matrix $D_\beta \Gamma_{g_1}$ is bounded on ℓ^2.*

Proof. Note that the diagonal matrix $D_\beta^{-1} = diag\left(\beta_j^{-1/2}\right)_{j\geq 0}$ is compact. So if $T_\varphi D_\beta$ is bounded, then T_φ is compact and this implies $\varphi = 0$. Therefore, no nonzero rank one operator of the form $1 \otimes g$ is a commutator. ☐

Remark. If we take $\beta_n = n+1$, then $H^2(\beta)$ is the Bergman space, L_a^2, and $g' \in \mathrm{Ext}_{A(D)}(L_a^2, H^2)$ if and only if the matrix $diag\left(\sqrt{n+1}\right)_{n\geq 0} \Gamma_g$ is bounded on ℓ^2. This happens if and only if the range of Γ_g is contained in the Dirichlet space $= H^2(\frac{1}{\beta})$. It is not hard to see that $\mathrm{Ext}_{A(D)}(L_a^2, H^2)$ contains all Bloch functions. In fact, if T is pointwise multiplication by z on L_a^2, then the operator W defined on polynomials by $W(p) = p(T^*)g$ is just the restriction of the little Hankel (with symbol g) on the Bergman space to H^2. It is well known that this operator is bounded on L_a^2 if and only if g is Bloch, see [8]. It will follow from a result in the next section that $\mathcal{M}(H^2, L_a^2)$ is also contained in $\mathrm{Ext}_{A(D)}(L_a^2, H^2)$.

5. A proof of Bourgain's result

Bourgain in [1] proved that the operator

$$R_f \quad = \quad \begin{pmatrix} S^* & \Gamma_f \\ 0 & S \end{pmatrix}$$

is similar to a contraction if $f' \in$ BMOA. In this section we will give an alternative proof of this result using subnormality and a characterization of BMOA in terms of Carleson measures on the Hardy space. What we will prove is the following:

(2)
$$f' \text{ is BMOA} \Longrightarrow \text{the matrix } A = \left((i+1)\hat{f}(i+j)\right)_{i,j\geq 0} \text{ is bounded on } \ell^2.$$

Note that if A is bounded, then $\Gamma_f = A - SAS = S^*(SA) - (SA)S$. Hence, R_f is similar to $S^* \oplus S$ via the similarity

$$\begin{pmatrix} I & SA \\ 0 & I \end{pmatrix}.$$

Proof of (2). ☐

Lemma 1. *Suppose that T is subnormal on a Hilbert space K and let $f \in K$. If $W(p) \equiv p(T)f$ extends to a bounded operator from H^2 into K, then the operator $V(p) \equiv p(T^*)f$ extends to a bounded operator from H^2 into K.*

Proof. The transpose of the matrix for W^*W is

$$B = \left(\langle T^{*j}T^i f, f\rangle_K\right)_{i,j\geq 0}$$

and the the matrix for V^*V is

$$C = \left(\langle T^i T^{*j} f, f\rangle_K\right)_{i,j\geq 0}.$$

By the Bram-Halmos criterion for subnormality, $B \geq C$. ☐

Remark. If $Tf(z) \equiv zf(z)$ is polynomially bounded on $H^2(\beta)$ and $\beta_n \longrightarrow \infty$, then by Corollary 3.2, $\mathrm{Ext}_{A(D)}(H^2(\beta), H^2)$ is the vector space of functions $g \in H^2(\beta)$ such that $p \mapsto p(T^*)g$ extends to a bounded operator from H^2 into $H^2(\beta)$. If we suppose further that T is subnormal, then it follows from Lemma 4.1 that $\mathcal{M}(H^2, H^2(\beta))$ is contained in $\mathrm{Ext}_{A(D)}(H^2(\beta), H^2)$.

By Nehari's theorem a function $f \in H^2$ is BMOA if and only if the Hankel matrix Γ_f is bounded on ℓ^2. Another useful criterion for f to be BMOA is that the measure $|f'(z)|^2 \log \frac{1}{|z|} dA(z)$ is Carleson for H^2, where A is normalized area measure on the disk. A good reference for this is Zhu's book [8]. Now what this means is that f' is a pointwise multiplier from H^2 into $\mathcal{P}^2(\mu)$, the closure of the analytic polynomials in $L^2(\mu)$, where $d\mu(z) = \log \frac{1}{|z|} dA(z)$. One verifies that $\frac{1}{(n+1)^2} = \int_D |z|^{2n} \log \frac{1}{|z|} dA(z)$ so that $\mathcal{P}^2(\mu) = H^2(\beta)$ with $\beta_n = (n+1)^2$, and multiplication by z is subnormal on this space. By the remark above $f' \in \mathrm{Ext}_{A(D)}(H^2(\beta), H^2)$. So by Proposition 4.1, the matrix

$$\left(\frac{i+1}{i+j+1}\hat{f}(i+j)\right)_{i,j\geq 0}$$

must be bounded on ℓ^2. If we repeat this argument with f' in place of f, we get that the matrix A is bounded. $\square$

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