HYPERRIGID GENERATORS IN C^* -ALGEBRAS

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ABSTRACT. In this article, we show that, if $S \in \mathcal{B}(H)$ is irreducible and essential unitary, then $\{S,SS^*\}$ is a hyperrigid generator for the unital C^* -algebra \mathcal{T} generated by $\{S,SS^*\}$. We prove that, if T is an operator in $\mathcal{B}(H)$ that generates an unital C^* -algebra \mathcal{A} then $\{T,T^*T,TT^*\}$ is a hyperrigid generator for \mathcal{A} . As a corollary it follows that, if $T \in \mathcal{B}(H)$ is normal then $\{T,TT^*\}$ is hyperrigid generator for the unital C^* -algebra generated by T and if $T \in \mathcal{B}(H)$ is unitary then $\{T\}$ is hyperrigid generator for the C^* -algebra generated by T. We show that if $V \in \mathcal{B}(H)$ is an isometry (not unitary) that generates the C^* -algebra \mathcal{A} then the minimal generating set $\{V\}$ is not hyperrigid for \mathcal{A} .

1. Introduction

The classical theorems of Korovkin impressed several mathematicians since their discovery for the simplicity and the potential. Positive approximation process play a fundamental role in the approximation theory and it appears in a very natural way in several problems dealing with the approximation of continuous functions and qualitative properties such as monotonicity, convexity, shape preservation and so on.

Korovkin [12] made a assertion that, if a sequence of positive linear maps $\phi_n: C[0,1] \to C[0,1], n=1,2,3,...$, has the property

$$\lim_{n \to \infty} ||\phi_n(f_k) - f_k|| = 0, \ k = 0, 1, 2,$$

for the three functions $f_0(x) = 1$, $f_1(x) = x$, $f_2(x) = x^2$ then

$$\lim_{n \to \infty} ||\phi_n(f) - f|| = 0, \ \forall \ f \in C[0, 1].$$

The set $\{1, x, x^2\}$ is called a *Korovkin set* or *test set*. Korovkin [12] showed that, the set $\{1, x\}$ is not a Korovkin set. Therefore, the set $\{1, x, x^2\}$ is a minimal set to satisfy the above assertion.

Korovkin's theorem generated considerable activity among researchers in approximation theory. The generalizations make essential use of the *Choquet boundary* in one way or another. Saskin [14] proved a remarkable theorem. Let G be a subset of C(X) that separates points of compact Hausdorff space X and contains constant function 1. Then G is a Korovkin set in C(X) if and only if the Choquet boundary ∂G of G is X. That is $\partial G = X$.

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Arveson [4] initiated the study of noncommutative approximation theory focusing on the question: How does one determine whether a set of generators of a C^* -algebra is *hyperrigid*? Arveson [4] introduced a noncommutative counterpart of Korovkin set as follows:

Definition 1.1. A finite or countably infinite set \mathcal{G} of generators of a C^* -algebra \mathcal{A} is said to be *hyperrigid* if for every faithful representation $\mathcal{A} \subseteq \mathcal{B}(H)$ of \mathcal{A} on a Hilbert space H and every sequence of unital completely positive (UCP) maps $\phi_n : \mathcal{B}(H) \to \mathcal{B}(H), n = 1, 2, ...,$

$$\lim_{n \to \infty} ||\phi_n(g) - g|| = 0, \ \forall \ g \in \mathcal{G} \Longrightarrow \lim_{n \to \infty} ||\phi_n(a) - a|| = 0, \ \forall \ a \in \mathcal{A}.$$

Note that, a set \mathcal{G} is hyperrigid if and only if $\mathcal{G} \cup \mathcal{G}^*$ is hyperrigid if and only if the linear span of \mathcal{G} is hyperrigid. If \mathcal{A} is unital, then \mathcal{G} is hyperrigid if and only if $\mathcal{G} \cup \{1\}$ is hyperrigid [15, Proposition 2.1].

The following characterization of hyperrigid operator systems due to Arveson [4] is more of a workable definition of hyperrigidity of operator systems.

Theorem 1.2. [4, Theorem 2.1] Let S be a separable operator system generating the C^* -algebra $A = C^*(S)$ then S is hyperrigid if and only if every nondegenerate representation $\pi : A \to \mathcal{B}(H)$ on a separable Hilbert space, $\pi|_{S}$ has the unique extension property in the sense that the only unital completely positive (UCP) map $\phi : A \to \mathcal{B}(H)$ that satisfies $\phi|_{S} = \pi|_{S}$ is $\phi = \pi$ itself.

The interesting examples of hyperrigid generators are obtained by a direct application of the above criterion. Arveson [4] established the noncommutative strengthening of a classical approximation-theoretic result of Korovkin.

Theorem 1.3. [4, Theorem 3.1] Let $X \in B(H)$ be a self adjoint operator with atleast 3 points in its spectrum and let A be the C^* -algebra generated by X. Then

- (i) $\mathcal{G} = \{X, X^2\}$ is a hyperrigid generator for \mathcal{A} , while
- (ii) $G_0 = \{X\}$ is not hyperrigid generator for A.

Theorem 1.4. [4, Theorem 3.3] Let $V \in \mathcal{B}(H)$ be an isometry that generates a C^* -algebra \mathcal{A} . Then $\mathcal{G} = \{V, VV^*\}$ is hyperrigid generator for \mathcal{A} .

Arveson [4] essentially used the noncommutative Choquet boundary. He found the hyperrigid generator for compact operators $\mathcal{K}(H)$.

Theorem 1.5. [4, Theorem 8.1] Let $V \in \mathcal{B}(H)$ be an irreducible compact operator with cartesian decomposition V = A + iB, where A is a finite rank positive operator and B is essential with $KerB = \{0\}$. Then

(i) $\mathcal{G} = \{V, V^2\}$ is hyperrigid generator for C^* -algebra $\mathcal{K}(H)$ of compact operators. In particular every sequence of unital completely positive maps $\phi_n : \mathcal{B}(H) \to \mathcal{B}(H)$ for which

$$\lim_{n \to \infty} ||\phi_n(V) - V|| = \lim_{n \to \infty} ||\phi_n(V^2) - V^2|| = 0,$$

one has

$$\lim_{n \to \infty} ||\phi_n(K) - K|| = 0$$

for every compact operator $K \in \mathcal{B}(H)$.

(ii) The smaller generating set $\mathcal{G}_0 = \{V\}$ of $\mathcal{K}(H)$ is not hyperrigid.

Let $S = (S_1, ..., S_d)$ denote the compression of the d-shift to the complement of a homogeneous ideal I of $\mathbb{C}[z_1, ..., z_d]$. Following the remark above, Kennedy and Shalit [9, Theorem 4.12] (see also [10]) proved that, if homogeneous ideals are sufficiently non-trivial then S is essentially normal if and only if it is hyperrigid as the generating set of a C^* -algebra.

The main purpose of this paper is to find the minimal hyperrigid generators for C^* -algebras. We show that, if $S \in \mathcal{B}(H)$ is irreducible and is an essential unitary and $\mathcal{G} = \{S, SS^*\}$. Let $\mathcal{T} = C^*(\mathcal{G})$ be the unital C^* -algebra generated by \mathcal{G} . Then \mathcal{G} is a hyperrigid generator for \mathcal{T} . We prove that, if T is an operator in $\mathcal{B}(H)$ that generates a unital C^* -algebra \mathcal{A} and $\mathcal{G} = \{T, T^*T, TT^*\}$, then \mathcal{G} is a hyperrigid generators for the unital C^* -algebra \mathcal{A} . As a corollary it follows that, if T be a normal operator in $\mathcal{B}(H)$ that generate a unital C^* -algebra \mathcal{A} and let $\mathcal{G} = \{T, TT^*\}$. Then \mathcal{G} is hyperrigid generator for unital C^* -algebra \mathcal{A} . If T be an unitary operator in $\mathcal{B}(H)$ that generate a C^* -algebra \mathcal{A} and let $\mathcal{G} = \{T\}$. Then \mathcal{G} is hyperrigid generator for C^* -algebra \mathcal{A} . We show that, if $V \in \mathcal{B}(H)$ be an isometry (not unitary) that generates a C^* -algebra \mathcal{A} . Then the minimal generating set $\mathcal{G}_0 = \{V\}$ is not hyperrigid generator for C^* -algebra \mathcal{A} .

2. Preliminaries

Here, we recall the necessary definitions, conventions and notations.

Let H be a separable complex Hilbert space and let $\mathcal{B}(H)$ be the set of all bounded linear operators on H. A operator system \mathcal{S} in a C^* -algebra \mathcal{A} is a self-adjoint linear subspace of \mathcal{A} containing the identity of \mathcal{A} . A operator algebra \mathcal{A}_0 in a C^* -algebra \mathcal{A} is a unital subalgebra of \mathcal{A} . Given a linear map ϕ from a C^* -algebra \mathcal{A} into a C^* -algebra \mathcal{B} we can define a family of maps $\phi_n : M_n(\mathcal{A}) \to M_n(\mathcal{B})$ given by $\phi_n([a_{ij}]) = [\phi(a_{ij})], n \in \mathbb{N}$. We say that ϕ is completely bounded (CB) if $||\phi||_{\text{CB}} = \sup_{n \geq 1} ||\phi_n|| < \infty$. We say that ϕ is isometric for all $n \geq 1$. We say that ϕ is completely positive (CP) if ϕ_n is positive for all $n \geq 1$, and that ϕ is unital completely positive (UCP) if in addition $\phi(1) = 1$.

Definition 2.1. Let S be an operator system that generates a C^* -algebra A. A unital completely positive map $\phi: S \to \mathcal{B}(H)$ is said to have the *unique extension property* if it has a unique extension to a UCP map $\widetilde{\phi}: A \to \mathcal{B}(H)$

The boundary representations of \mathcal{A} for \mathcal{S} , which were introduced by Arveson [1], are precisely the irreducible representations $\pi: \mathcal{A} \to \mathcal{B}(H)$ with the property that the restriction $\pi_{|\mathcal{S}|}$ has the unique extension property. The existence of boundary representations was an open question for some time. Arveson [3] proved the existence of boundary representations for separable C^* -algebras. Davidson and Kennedy [7] settled the existence of boundary representations for general C^* -algebras.

Arveson [4] tried to prove the non-commutative analogue of Saskin's theorem [14] using theory of noncommutative Choquet boundary for unital completely positive maps on C^* -algebras and noncommutative counterpart of the Korovkin's

set which is the hyperrigid set. Arveson [4] proved that if the separable operator system is hyperrigid in the C^* -algebra then every irreducible representation of C^* -algebra is a boundary representation for the operator system. The converse to this result is called *hyperrigidity conjecture*: that is, if every irreducible representation of a C^* -algebra is a boundary representation for a separable operator system then the operator system is hyperrigid.

Arveson [4] showed that the hyperrigidity conjecture is true for C^* -algebras with countable spectrum. Kleski [11] established the hyperrigidity conjecture for all type-I C^* -algebras with additional assumptions on the co-domain. Davidson and Kennedy[8] proved the conjecture for function systems. Clouatre [6] established the hyperrigidity conjecture with assumption of unperforated. The hyperrigidity conjecture is still open for general C^* -algebras. Namboodiri, Pramod, Shankar and Vijayarajan [13] approached the hyperrigidity conjecture with weaker notions. They got the partial answers.

3. Essential Unitary and hyperrigidity

Let $\mathcal{B}(H)$ be the algebra of bounded linear operators on a separable complex Hilbert space H and $\mathcal{K}(H)$ ideal of compact operators on H. Let $\pi: \mathcal{B}(H) \to \mathcal{B}(H)/\mathcal{K}(H)$ be the natural surjection onto the Calkin algebra $\mathcal{B}(H)/\mathcal{K}(H)$. The operator $T \in \mathcal{B}(H)$ is called essentially normal if $\pi(T)$ is normal in the Clakin algebra, or equivalently, $T^*T - TT^*$ is compact. The operator $S \in \mathcal{B}(H)$ is called essentially unitary if $\pi(S)$ is unitary in the Clakin algebra, or equivalently, $I - S^*S$ and $I - SS^*$ are compact. The above definitions can be found in [5].

Here, we will have the following assumptions to proceed. Let S be a irreducible and essential unitary but not unitary operator in $\mathcal{B}(H)$ and let $\mathcal{G} = \{S, SS^*\}$. Let S be a operator system generated by G. Let $T = C^*(G)$ be the unital C^* -algebra generated by G. The unital C^* -algebra T contains the compact operators K(H).

A representation $\rho: \mathcal{T} \to \mathcal{B}(H)$ is said to be singular representation if it annihilates the compact operators $\mathcal{K}(H)$.

Lemma 3.1. Let $\rho: \mathcal{T} \to \mathcal{B}(H)$ be a representation, and let $\pi: \mathcal{T} \to \mathcal{B}(K)$ be a representation such that $\pi|_{\mathcal{S}}$ is a dilation of $\rho|_{\mathcal{S}}$. Then the subspace H is coinvariant for $\pi(\mathcal{S})$.

Proof. With respect to the decomposition $K = H \oplus H^{\perp}$. By assumption we have

$$\pi(S) = \left(\begin{array}{cc} \rho(S) & X \\ Y & Z \end{array}\right)$$

Note that $X = P_H \pi(S)|_{H^{\perp}}$. We must prove that X = 0. By assumption,

$$\begin{pmatrix} \rho(SS^*) & X_0 \\ Y_0 & Z_0 \end{pmatrix} = \pi(SS^*) = \pi(S)\pi(S)^* = \begin{pmatrix} \rho(S) & X \\ Y & Z \end{pmatrix} \begin{pmatrix} \rho(S)^* & Y^* \\ X^* & Z^* \end{pmatrix}.$$

We get,

$$\rho(SS^*) = \rho(S)\rho(S)^* + XX^*$$

Therefore, $XX^* = 0$, and hence X = 0.

Proposition 3.2. Suppose that S is irreducible and essential unitary and $\mathcal{G} = \{S, SS^*\}$. Let S be a operator system generated by \mathcal{G} and $\mathcal{T} = C^*(\mathcal{G})$. Let $\rho : \mathcal{T} \to \mathcal{B}(H)$ be a singular representation. Then the restriction $\rho|_{\mathcal{S}}$ has unique extension property.

Proof. We will use the fact that a UCP map ϕ' has the unique extension property if and only if ϕ' is maximal, meaning that every UCP map that dilates ϕ' contains as a direct summand [3, Proposition 2.4].

Let K be a Hilbert space properly containing H. Let $\pi: \mathcal{T} \to \mathcal{B}(K)$ be a representation such that the restriction $\pi|_{\mathcal{S}}$ is a dilation of $\rho|_{\mathcal{S}}$. To show that the restriction $\rho|_{\mathcal{S}}$ has unique extension property, it is enough to show that the dilation π is trivial, that is, $\pi|_{\mathcal{S}} = \rho|_{\mathcal{S}} \oplus \phi$ for some UCP map ϕ .

Using the Lemma 3.1, we can decompose $K = H \oplus H^{\perp}$ and write

$$\pi(S) = \left(\begin{array}{cc} \rho(S) & 0\\ Y & Z \end{array}\right).$$

Since ρ is singular, $\rho(S)$ is unitary, so it cannot be dilated to a compression. Therefore the dilation π must be trivial.

Proposition 3.3. Suppose that S is irreducible and essential unitary and $\mathcal{G} = \{S, SS^*\}$. Let S be a operator system generated by \mathcal{G} and $\mathcal{T} = C^*(\mathcal{G})$. Then the identity representation of \mathcal{T} is a boundary representation for S.

Proof. Since S is irreducible and essential unitary. The unital C^* -algebra generated by \mathcal{G} contains the compact operators, that is, $\mathcal{K}(H) \subseteq \mathcal{T} = C^*(\mathcal{G})$. The operator system $\mathcal{S} \subset \mathcal{T}$ is irreducible and contains the identity operator. By our assumption, $0 \neq \mathcal{K} = I - SS^* \in \mathcal{S}$ is a compact operator, we have $||\mathcal{K} - \mathcal{K}|| < ||\mathcal{K}||$. Therefore, the quotient map $q : \mathcal{B}(H) \to \mathcal{B}(H)/\mathcal{K}(H)$ is not completely isometric on \mathcal{S} . Hence by boundary theorem of Arveson [2, Theorem 2.1.1], identity representation of \mathcal{T} is a boundary representation for \mathcal{S} .

Theorem 3.4. Let S be an irreducible and essential unitary and $\mathcal{G} = \{S, SS^*\}$. Let $\mathcal{T} = C^*(\mathcal{G})$ be the unital C^* -algebra generated by \mathcal{G} . Then \mathcal{G} is a hyperrigid generator for \mathcal{T} .

Proof. Let S be the operator system generated by G. Note that G is hyperrigid if and only if S is hyperrigid. By Theorem 1.2, it suffices to show that for every nondegenerate representation ρ of T, $\rho|_{S}$ has the unique extension property.

The Proposition 3.2 implies that every singular nondegenerate representation π of \mathcal{T} , $\pi|_{\mathcal{S}}$ has the unique extension property. By Proposition 3.3, the restriction of the identity representation of \mathcal{T} to \mathcal{S} has the unique extension property. Since every nondegenerate representation of \mathcal{T} splits as the direct sum of a multiple of the identity representation and a singular nondegenerate representation and by [4, Proposition 4.4] the unique extension property passes to direct sums. Hence every nondegenerate representation of \mathcal{T} restricted to \mathcal{S} has the unique extension property.

Example 3.5. Let H be a Hilbert space having an orthonormal basis $\{e_n : n \geq 0\}$. The unilateral shift S is defined by $Se_n = e_{n+1}$. The C^* -algebra

 \mathcal{T} generated by S is called the Toeplitz C^* -algebra. Observe that $I - S^*S$ and $I - SS^*$ are compact, therefore S is essential unitary. Also, S is irreducible. The Toeplitz C^* -algebra \mathcal{T} contains the compact operators $\mathcal{K}(H)$. We know that the set $\{S, SS^*\}$ also generates the Toeplitz C^* -algebra \mathcal{T} . Hence, by Theorem 3.4, The set $\{S, SS^*\}$ is hyperrigid generator for Toeplitz C^* -algebra \mathcal{T} .

4. Hyperrigid generators

The main purpose of this section is to find the hyperrigid generators for the C^* -algebras generated by a single operator.

Theorem 4.1. Let T be an operator in $\mathcal{B}(H)$ that generate a unital C^* -algebra \mathcal{A} and let $\mathcal{G} = \{T, T^*T, TT^*\}$. Then \mathcal{G} is hyperrigid generators for unital C^* -algebra \mathcal{A} .

Proof. Let S be the operator system generated by G. By Theorem 1.2, it suffices to show that for every nondegenerate representation π of A, $\pi|_{S}$ has the unique extension property.

Let $\pi: \mathcal{A} \to \mathcal{B}(H)$ be a nondegenerate representation. Let $\phi: \mathcal{A} \to \mathcal{B}(H)$ be a UCP map satisfying $\phi(T) = \pi(T), \phi(T^*T) = \pi(T^*T)$ and $\phi(TT^*) = \pi(TT^*)$. We have to show that $\phi = \pi$ on \mathcal{A} .

Using Stinespring theorem, we can express ϕ in the form

$$\phi(S) = V^* \sigma(S) V, \ \forall \ S \in \mathcal{A}.$$

Where σ is a representation of A on a Hilbert space $K, V : H \to K$ is an isometry, and which is minimal in the sense that $\overline{\sigma(A)VH} = K$.

We first claim that $\sigma(T)V = V\pi(T)$, We have

$$V^* \sigma(T)^* V V^* \sigma(T) V = \phi(T)^* \phi(T) = \pi(T)^* \pi(T) = \pi(T^*T)$$

Hence.

$$V^*\sigma(T)^*(1 - VV^*)\sigma(T)V = V^*\sigma(T)^*\sigma(T)V - V^*\sigma(T)^*VV^*\sigma(T)V$$

= $V^*\sigma(T^*T)V - \pi(T)^*\pi(T)$
= $\pi(T^*T) - \pi(T^*T) = 0$.

 $\sigma(T)$ leaves VH invariant. Therefore $\sigma(T)V = VV^*\sigma(T)V = V\phi(T) = V\pi(T)$.

$$\begin{array}{lcl} VV^*\sigma(T)(1_K-VV^*)\sigma(T)^*VV^* & = & VV^*\sigma(T)\sigma(T)^*VV^* \\ & & -VV^*\sigma(T)VV^*\sigma(T)^*VV^* \\ & = & VV^*\sigma(TT^*)VV^* - V\pi(T)\pi(T)^*V^* \\ & = & V\pi(TT^*)V^* - V\pi(TT^*)V^* = 0. \end{array}$$

Hence $(1_K - VV^*)\sigma(T)^*VV^* = 0$, we conclude that VH is invariant under both $\sigma(T)$ and $\sigma(T)^*$. Since \mathcal{A} is generated by T it follows that $\sigma(\mathcal{A})VH \subseteq VH$. By minimality we must have VH = K, which implies that V is unitary and therefore $\phi(S) = V^{-1}\sigma(S)V$ is a representation. Since ϕ agrees with π on a generating set. Therefore $\phi = \pi$ on \mathcal{A} .

Corollary 4.2. Let T be a normal operator in $\mathcal{B}(H)$ that generate a unital C^* -algebra \mathcal{A} and let $\mathcal{G} = \{T, TT^*\}$. Then \mathcal{G} is hyperrigid generator for unital C^* -algebra \mathcal{A} .

Corollary 4.3. Let T be an unitary operator in $\mathcal{B}(H)$ that generate a C^* -algebra \mathcal{A} and let $\mathcal{G} = \{T\}$. Then \mathcal{G} is hyperrigid generator for C^* -algebra \mathcal{A} .

Proposition 4.4. Let $V \in \mathcal{B}(H)$ be an isometry (not unitary) that generates a C^* -algebra \mathcal{A} . Then

- (i) $\mathcal{G} = \{V, VV^*\}$ is hyperrigid generator for \mathcal{A} .
- (ii) The smaller generating set $\mathcal{G}_0 = \{V\}$ is not hyperrigid.

Proof. (i) follows from the Theorem 1.4. Now we will prove (ii), let S be the operator system generated by G_0 . Let Id denote the identity representation of a C^* -algebra A. Let $V^*Id(\cdot)V$ be a completely positive map on the C^* -algebra A. We have $V^*IdV|_{S} = Id|_{S}$, but

$$V^*Id(VV^*)V = I \neq VV^* = Id(VV^*).$$

This implies that Id representation restricted to \mathcal{S} has two UCP map extensions V^*IdV and Id. Therefore the nondegenerate representation $Id|_{\mathcal{S}}$ does not have unique extension property. Using the Theorem 1.2, \mathcal{S} is not hyperrigid operator system in a C^* -algebra \mathcal{A} . This will imply that \mathcal{G}_0 is not hyperrigid in \mathcal{A} .

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