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Submodules of $L^2(\mathbb{R}^2)$

MICHIO SETO

Abstract
In this paper, we study submodules over $\mathbb{R}^2$. We will give a Lax-type of theorem and a result analogous to Helson’s theory.


Keywords and phrases: Hardy submodules.

1 Introduction

$L^2(\mathbb{R}^2)$ will denote the Hilbert space of square-integrable measurable functions with respect to the usual Lebesgue measure $dx_1dx_2$ on the two dimensional Euclidean space $\mathbb{R}^2$. $H^2(\mathbb{R})$ denotes the usual Hardy space on $\mathbb{R}$, that is, $H^2(\mathbb{R})$ consists of all functions in $L^2(\mathbb{R})$ which can be extended analytically to the upper half plane $\mathbb{C}_+ = \{x + it : x \in \mathbb{R}, t > 0\}$. $H^2(\mathbb{R}) \otimes H^2(\mathbb{R})$, the Hilbert space tensor product of $H^2(\mathbb{R})$, is the space of all $f$ in $L^2(\mathbb{R}^2)$ whose Fourier transform

$$\hat{f}(\lambda_1, \lambda_2) = \int_{\mathbb{R}^2} f(x_1, x_2) e^{-i(\lambda_1 x_1 + \lambda_2 x_2)} dx_1 dx_2$$

is 0 whenever at least one component of $(\lambda_1, \lambda_2)$ is negative, where $(\lambda_1, \lambda_2)$ and $(x_1, x_2)$ are in $\mathbb{R}^2$. In this paper, $H^2(\mathbb{R}) \otimes H^2(\mathbb{R})$ is denoted by $H^2(\mathbb{R}^2)$, for short. Note that our $H^2(\mathbb{R}^2)$ is different from the usual Hardy space on $\mathbb{R}^2$.

Definition 1.1 A closed subspace $\mathcal{M}$ of $L^2(\mathbb{R}^2)$ is said to be a submodule of $L^2(\mathbb{R}^2)$ if $e^{ixj} \mathcal{M} \subseteq \mathcal{M}$ for any $j = 1, 2$ and any $s \geq 0$. For $s \geq 0$, $S_j(s)$ denotes the restriction on $\mathcal{M}$ of the multiplication operator on $L^2(\mathbb{R}^2)$ by $e^{ixj}$.

Submodules in one variable were completely described by Lax in [4]. In [1], Helson gave another point of view to the result of Lax. The purpose of our study is to consider Helson’s theory in the multi-variable setting. My interest in considering Helson’s theory in two variables is motivated by the study of Hardy submodules over the bidisk: Hardy submodules are invariant subspaces of Hardy space under multiplication operators by
bounded analytic functions. However, it is easy to see that a straightforward generalization of Helson's theory fails in the multi-variable setting. In Section 2 of this paper, we give a Lax-type theorem in two variables. To prove this we use Masani's integral (cf. [6]). In Section 3, we consider Helson's theory in two variables. We will give a result analogous to Helson's result under the following condition: \( S_1(s)S_2(t)^* = S_2(t)^*S_1(s) \) for all \( s, t \geq 0 \).

## 2 A Lax-type of theorem in \( \mathbb{R}^2 \)

In [9], the author showed the following Lax-type of theorem analogous to the theorem proved by Mandrekar [5] and Nakazi [7] for the bitorus.

**Theorem 2.1** Let \( \mathcal{M} \) be a submodule of \( L^2(\mathbb{R}^2) \), \( H^2_{x_1}(\mathbb{R}^2) = L^2(\mathbb{R}, dx_1) \otimes H^2(\mathbb{R}, dx_2) \) and \( H^2_{x_2}(\mathbb{R}^2) = H^2(\mathbb{R}, dx_2) \otimes L^2(\mathbb{R}, dx_1) \). If \( S_1(s)S_2(t)^* = S_2(t)^*S_1(s) \) for all \( s, t \geq 0 \), then one and only one of the following occurs:

(i) \( \mathcal{M} = \chi_E L^2(\mathbb{R}^2) \oplus \chi_F \varphi H^2_{x_1}(\mathbb{R}^2) \),

(ii) \( \mathcal{M} = \chi_E L^2(\mathbb{R}^2) \oplus \chi_G \psi H^2_{x_2}(\mathbb{R}^2) \),

(iii) \( \mathcal{M} = q H^2(\mathbb{R}^2) \),

where \( \varphi, \psi \) and \( q \) are unimodular functions, \( \chi_E \) is the characteristic function of \( E \), \( \chi_F \) (resp. \( \chi_G \)) is the characteristic function of \( F \) (resp. \( G \)) which depends only on the variable \( x_1 \) (resp. \( x_2 \)).

We shall give a proof which differs from that given in [9]. To begin with, we briefly introduce Masani’s integral which can be seen as a continuous Wold decomposition for a continuous semi-group of isometries, according to [6].

**Definition 2.1 (Masani [6])** Let \( \{S(t) : t \geq 0\} \) be a strongly continuous semi-group of isometries on a Hilbert space \( \mathcal{H} \). We introduce an operator-valued interval-measure. The measure \( T_{ab} \) of the interval \([a, b]\) is defined by as follows:

\[
T_{[a,b]} = T(b) - T(a), \text{ where } T(t) = \frac{1}{\sqrt{2}} \left\{ S(t) - I - \int_0^t S(s) \, ds \right\}, \text{ for } t \geq 0.
\]

Let \( iH \) be the infinitesimal generator of \( \{S(t) : t \geq 0\} \) and \( V \) be the Cayley transform of \( H \) and \( R = V(\mathcal{H}) \). For the step-function \( x = \sum_{k=1}^n \alpha_k \chi_{J_k} \) on \([a, b]\), where \( \alpha_k \) in \( R^1 \) and \( \chi_{J_k} \) is the characteristic function of bounded interval \( J_k \), we define

\[
\int_a^b T_{dt}(x_t) := \sum_{k=1}^n T_{J_k}(\alpha_k).
\]
For any $x$ in $L^2([a, b], R^2)$, we define
\[
\int_a^b T_{dt}(x_t) := \lim_{n \to \infty} \int_a^b T_{dt}(x_t^n),
\]
where $\{x_t^n, n \geq 1\}$ is any sequence of step-functions which is tending to $x$ in the $L^2$-topology.

We now define a direct integral as a set of vector-valued integrals:
\[
\int_a^b T_{dt}(R^1) := \left\{ \xi : \xi = \int_a^b T_{dt}(x_t), x \in L^2([a, b], R^1) \right\}.
\]

**Theorem 2.2 (Masani [6])** Let $\{S(t) : t \geq 0\}$ be a strongly continuous semi-group of isometries on a Hilbert space $\mathcal{H}$, $iH$ be its infinitesimal generator and let $V$ be the Cayley transform of $H$. Then, for $a \geq 0$,
\[
S(a)(\mathcal{H}) = \int_a^\infty T_{dt}(R^1) \oplus \mathcal{H}_\infty,
\]
where $R = V(\mathcal{H})$ and $\mathcal{H}_\infty = \bigcap_{t \geq 0} S(t)(\mathcal{H})$.

This theorem can be seen as a continuous Wold decomposition.

**Example 2.1** Let $T_{ds}^{(k)}$ be the operator-valued measures defined by $S_k(s)$ for $k = 1, 2$. Identifying bounded functions with multiplication operators, $T^{(k)}(s)$ can be computed formally as follows:
\[
T^{(k)}(s) = \frac{1}{\sqrt{2}} \left\{ S_k(s) - I_{\mathcal{M}} - \int_0^s S_k(t) \, dt \right\}
\]
\[
= \frac{1}{\sqrt{2}} \left\{ e^{isx_k} - 1 - \int_0^s e^{itx_k} \, dt \right\}
\]
\[
= \frac{1}{\sqrt{2}} \left\{ e^{isx_k} - 1 - \left[ \frac{1}{ix_k} e^{itx_k} \right]_0^s \right\}
\]
\[
= \frac{1}{\sqrt{2}} \left\{ e^{isx_k} - 1 - \frac{1}{ix_k} \left( e^{isx_k} - 1 \right) \right\}
\]
\[
= \frac{1}{\sqrt{2}} \left( e^{isx_k} - 1 \right) \left( 1 - \frac{1}{ix_k} \right)
\]
\[
= \frac{1}{\sqrt{2}} x_k \left( e^{isx_k} - 1 \right) (x_k + i).
\]

Thus the operator valued measure $T_{ds}^{(k)}$ can be computed as follows:
\[
T_{ds}^{(k)} = \frac{d}{ds} \left( \frac{1}{\sqrt{2}} x_k \left( e^{isx_k} - 1 \right) (x_k + i) \right) \, ds
\]
\[
= \frac{1}{\sqrt{2}} e^{isx_k} (x_k + i) \, ds.
\]

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We are now in a position to prove Theorem 2.1.

**Proof (A proof of Theorem 2.1)** Some parts of this proof are similar to those in the proof by Mandrekar [5] and Nakazi [7] for the bitorus (cf. Seto [9]).

Suppose that $S_1(s)S_2(t)^* = S_2(t)^*S_1(s)$ for all $s, t \geq 0$. Let $V_{x_k}$ be the isometry induced by $\{S_k(s) : s \geq 0\}$ as in Theorem 2.2 for $k = 1, 2$. Since $V_{x_k}$ is in the von Neumann algebra generated by $\{S_k(s) : s \geq 0\}$, we have $V_{x_1}^*V_{x_2} = V_{x_2}V_{x_1}^*$. It suffices to consider the following two cases:

- $V_{x_1}$ and $V_{x_2}$ are completely non-unitary,
- $V_{x_1}$ is completely non-unitary and $V_{x_2}$ is unitary.

First, we suppose that $V_{x_1}$ and $V_{x_2}$ are completely non-unitary. Then

$$\mathcal{M} = \int_0^\infty T_{ds}^{(1)} \left\{ \int_0^\infty T_{dt}^{(2)} (\mathcal{M} \oplus (V_{x_1} \mathcal{M} + V_{x_2} \mathcal{M})) \right\} ,$$

by Theorem 2.2. Let $f$ be in $\mathcal{M} \oplus (V_{x_1} \mathcal{M} + V_{x_2} \mathcal{M})$ such that $\|f\| = 1$. Then

$$\int_{\mathbb{R}^2} |f(x_1, x_2)|^2 \frac{(x_1 - i)^k (x_2 - i)^l}{(x + i)^k (x + i)^l} \; dx_1 dx_2 = 0,$$

for all $(k, l) \neq (0, 0)$. Changing variables $x_1$ and $x_2$ to $\theta_1$ and $\theta_2$, we have

$$\int_0^{2\pi} \int_0^{2\pi} |f(\theta_1, \theta_2)|^2 e^{ik\theta_1} e^{il\theta_2} \frac{1}{\cos^2 \frac{\theta_1}{2} \cos^2 \frac{\theta_2}{2}} \; d\theta_1 d\theta_2 = 0.$$

Hence $|f(\theta_1, \theta_2)|^2 (\cos^2 \frac{\theta_1}{2})^{-1} (\cos^2 \frac{\theta_2}{2})^{-1} = 1$, equivalently $(x_1^2 + 1)(x_2^2 + 1)|f(x_1, x_2)|^2 = 1$.

Therefore, there exists a unimodular function $q$ such that

$$f = \frac{q}{(x_1 + i)(x_2 + i)}.$$

Hence we have

$$\mathcal{M} \oplus (V_{x_1} \mathcal{M} + V_{x_2} \mathcal{M}) = C \frac{q}{(x_1 + i)(x_2 + i)}.$$

By the Paley-Wiener theorem,

$$\mathcal{M} = \int_0^\infty T_{ds}^{(1)} \left\{ \int_0^\infty T_{dt}^{(2)} \left( C \frac{q}{(x_1 + i)(x_2 + i)} \right) \right\}$$

$$= \left\{ \xi : \xi = q \int_0^\infty e^{ix_1} ds \int_0^\infty e^{ix_2} f(s, t) \; dt ; f \in L^2((0, \infty) \times (0, \infty)) \right\}$$

$$= q \left(H^2(\mathbb{R}) \otimes H^2(\mathbb{R}) \right)$$

$$= qH^2(\mathbb{R}^2).$$

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Next, we suppose that $V_{x_1}$ is completely non-unitary and $V_{x_2}$ is unitary. Then

$$\mathcal{M} = \int_0^\infty T_{ds}^{(1)} (\mathcal{M} \ominus V_{x_1}, \mathcal{M}),$$

by Theorem 2.2. Let $f$ be in $\mathcal{M} \ominus V_{x_1} \mathcal{M}$. Then

$$\int_{\mathbb{R}^2} |f(x_1, x_2)|^2 \frac{(x_1 - i)^k (x_2 - i)^l}{(x_1 + i)^k (x_2 + i)^l} \, dx_2 \, dx_1 = 0,$$

for all $k \neq 0$ and $l$. By the same calculations as in the first case, we have

$$f(x_1, x_2) = \frac{g(x_1, x_2)}{(x_1 + i)}$$

for some $g$ such that the function $|g|$ depends only on the variable $x_2$.

The following argument is known (cf. [3]). Let $\chi_{E(g)}$ be the support function of $g$, that is, $\chi_{E(g)}$ is the characteristic function of the set $E(g) = \{(x_1, x_2) \in \mathbb{R}^2 : g(x_1, x_2) \neq 0\}$, and $\phi_g$ be a unimodular function defined as follows:

$$\phi_g = \begin{cases} \frac{|g|}{g} & (g \neq 0) \\ 1 & (g = 0). \end{cases}$$

Then

$$\bigvee_{i \in \mathbb{R}} e^{ix_2} \frac{g}{x_1 + i} = \frac{\phi_g}{x_1 + i} \chi_{E(g)} L^2(\mathbb{R}, dx_2),$$

where $\bigvee$ denotes the closed vector span. Since there exists a function $F$ in $\mathcal{M} \ominus V_{x_1} \mathcal{M}$ which has the maximal support in $\mathcal{M} \ominus V_{x_1} \mathcal{M}$, that is, $E(g) \subseteq E(F)$, for any $g$ in $\mathcal{M} \ominus V_{x_1} \mathcal{M}$, we have

$$\mathcal{M} \ominus V_{x_1} \mathcal{M} = \phi_F L^2(\mathbb{R}, dx_2).$$

Let $\chi_G = \chi_{E(F)}$ and $\psi = \phi_F$. By the Paley-Wiener theorem, we have the following:

$$\mathcal{M} = \int_0^\infty T_{ds}^{(1)} \left( \frac{1}{x_1 + i} \chi_G \psi L^2(\mathbb{R}, dx_2) \right)$$

$$= \left\{ \xi : \xi = \chi_G \psi \int_0^\infty e^{ix_2} f(s, x_2) \, ds ; f \in L^2((0, \infty) \times \mathbb{R}) \right\}$$

$$= \chi_G \psi H^2(\mathbb{R}, dx_1) \otimes L^2(\mathbb{R}, dx_2)$$

$$= \chi_G \psi H^2_{x_2}(\mathbb{R}^2).$$

The converse is easy to verify.

A function $q$ is said to be inner if $q$ is in $H^2(\mathbb{R}^2)$ and $|q(x_1, x_2)| = 1$ a.e.

**Corollary 2.1** Let $\mathcal{M}$ be a submodule of $H^2(\mathbb{R}^2)$. Then $S_1(s) S_2(t)^* = S_2(t)^* S_1(s)$ for all $s, t \geq 0$ if and only if $\mathcal{M} = qH^2(\mathbb{R}^2)$ for some inner function $q$.  


3 Helson’s theory under the double commuting condition in $L^2(\mathbb{R}^2)$

In this section, we discuss Helson’s theory in $L^2(\mathbb{R}^2)$ under the double commuting condition: $S_1(s)S_2(t)^* = S_2(t)^*S_1(s)$ for all $s, t \geq 0$. Then, it is parallel to Helson’s argument for the one-variable case in [1].

**Definition 3.1** Let $\mathcal{M}$ be a submodule of $L^2(\mathbb{R}^2)$. For any $\lambda, \mu$ in $\mathbb{R}$, we define one-parameter unitary groups $\{\alpha_\lambda\}$, $\{\beta_\mu\}$ and projections $\{P_\lambda\}$, $\{Q_\mu\}$ on $L^2(\mathbb{R}^2)$ as follows: for any $f$ in $L^2(\mathbb{R}^2)$, $\alpha_\lambda f = e^{i\lambda x} f$, $\beta_\mu f = e^{i\mu y} f$, and $P_\lambda = \alpha_\lambda^* P_\lambda \alpha_\lambda$, $Q_\mu = \beta_\mu^* P_\lambda \beta_\mu$, that is, $P_\lambda$ and $Q_\mu$ are the orthogonal projections of $L^2(\mathbb{R}^2)$ onto $\alpha_\lambda^* \mathcal{M}$ and $\beta_\mu^* \mathcal{M}$, respectively.

**Lemma 3.1** Let $\mathcal{M}$ be a submodule of $L^2(\mathbb{R}^2)$. $S_1(s)S_2(t)^* = S_2(t)^*S_1(s)$ for all $s, t \geq 0$ if and only if $P_\lambda \alpha_\lambda P_\lambda \beta_\mu P_\lambda = P_\lambda \beta_\mu P_\lambda \alpha_\lambda P_\lambda$ for all $\lambda, \mu$ in $\mathbb{R}$.

**Proof** It is easy to verify.

**Definition 3.2** A submodule $\mathcal{M}$ of $L^2(\mathbb{R}^2)$ is said to be simple if $S_1(s)S_2(t)^* = S_2(t)^*S_1(s)$ for all $s, t \geq 0$ and $\left(\bigcap_\lambda \alpha_\lambda \mathcal{M} + \bigcap_\mu \beta_\mu \mathcal{M}\right) = \{0\}$ (this is equivalent to that $P_{-\infty} = \lim_{\lambda \to -\infty} P_\lambda = O$ and $Q_{-\infty} = \lim_{\mu \to -\infty} Q_\mu = O$).

Note that a submodule $\mathcal{M}$ is simple if and only if $\mathcal{M} = qH^2(\mathbb{R}^2)$ for some unimodular function $q$ by Theorem 2.2.

Next, we define two sequences of projections, and show that these are the spectral measures of $L^2(\mathbb{R}^2)$. Let $E_\lambda$ and $F_\mu$ be projections defined as follows:

$$E_\lambda = \alpha_\lambda^* Q_{+\infty} \alpha_\lambda \quad \text{and} \quad F_\mu = \beta_\mu^* P_{+\infty} \beta_\mu.$$

**Lemma 3.2** Let $\mathcal{M}$ be a submodule of $L^2(\mathbb{R}^2)$. If $\mathcal{M}$ is simple, then $\{E_\lambda\}$ and $\{F_\mu\}$ are spectral families. Moreover $E_\lambda F_\mu = F_\mu E_\lambda = \alpha_\lambda^* \beta_\mu^* P_\lambda \alpha_\lambda \beta_\mu$ for all $\lambda, \mu$ in $\mathbb{R}$.

**Proof** Since, for $\gamma \geq \lambda, \mu$,

$$E_\lambda F_\mu = \alpha_\lambda^* Q_{+\infty} \alpha_\lambda \beta_\mu^* P_{+\infty} \beta_\mu = \lim_{\gamma \to +\infty} \left(\alpha_\gamma^* \beta_\gamma^* P_\gamma \alpha_\gamma \beta_\gamma^* \alpha_\gamma^* \beta_\gamma^* P_\gamma \alpha_\gamma \beta_\gamma^*\right) = \lim_{\gamma \to +\infty} \left(\alpha_\gamma^* \beta_\gamma^* P_\gamma \alpha_\gamma \beta_\gamma^* P_\gamma \alpha_\gamma \beta_\gamma^*\right) = \lim_{\gamma \to +\infty} \left(\alpha_\gamma^* \beta_\gamma^* P_\gamma \alpha_\gamma \beta_\gamma^* P_\gamma \alpha_\gamma \beta_\gamma^*\right) = \alpha_\lambda^* \beta_\mu^* P_\lambda \alpha_\lambda \beta_\mu.$$
we have \( E_\lambda F_\mu = \alpha_{\lambda\beta}^* P_M \alpha_{\lambda\beta} = F_\mu E_\lambda \) for all \( \lambda, \mu \) in \( \mathbb{R} \).

Next, suppose that

\[
\chi_G L^2(\mathbb{R}^2) = \bigcup_{\lambda, \mu} \alpha_{\lambda\beta}^* P_M \alpha_{\lambda\beta} M \bigcap \bigcup_{\lambda} \alpha_{\lambda\mu} \bigcap \bigcup_{\mu} \beta_{\mu} \bigcup_{\lambda} \alpha_{\lambda\mu} M,
\]

where the bar denotes the closure. We shall show \( \chi_G = 1 \). The following argument is the same as in [1]. Let \( U_{s,0} = \int_\mathbb{R} e^{i\lambda x} dE_\lambda \). Then, since \( \alpha_{\lambda\mu} e_{\lambda\mu} = \alpha_{\lambda\mu} \beta_{\mu} e_{\lambda\mu} = E_{\lambda - \lambda_0} \), we have

\[
\alpha_{\lambda\mu} e_{\lambda\mu} U_{s,0} = \alpha_{\lambda\mu} e_{\lambda\mu} \int_\mathbb{R} e^{i\lambda x} dE_\lambda = \int_\mathbb{R} e^{i\lambda x} dE_{\lambda - \lambda_0} \alpha_{\lambda\mu} e_{\lambda\mu} = e^{i\lambda \lambda_0} \int_\mathbb{R} e^{i\lambda (\lambda - \lambda_0)} dE_{\lambda - \lambda_0} \alpha_{\lambda\mu} e_{\lambda\mu} = e^{i\lambda \lambda_0} U_{s,0} \alpha_{\lambda\mu} e_{\lambda\mu}.
\]

Therefore

\[
U_{s,0} T_{-s,0} \alpha_{\lambda\mu} = U_{s,0} e^{i\lambda \lambda_0} \alpha_{\lambda\mu} \alpha_{\lambda\mu} T_{-s,0} = \alpha_{\lambda\mu} U_{s,0} T_{-s,0},
\]

where \( T_{-s,t} \) is the translation operator such that \( (T_{s,t} f)(x, y) = f(x - s, y - t) \). Hence \( U_{s,0} T_{-s,0} \) is a multiplication operator on \( L^2(\mathbb{R}^2) \). Since \( U_{s,0} T_{-s,0} \) maps \( T_{s,0} \chi_G L^2(\mathbb{R}^2) \) to \( \chi_G L^2(\mathbb{R}^2) \), we have \( T_{s,0} \chi_G L^2(\mathbb{R}^2) = \chi_G L^2(\mathbb{R}^2) \). By the same argument for \( \beta_{\mu} \), we have \( T_{0,\mu} \chi_G L^2(\mathbb{R}^2) = \chi_G L^2(\mathbb{R}^2) \), that is, \( T_{s,t} \chi_G L^2(\mathbb{R}^2) = L^2(\mathbb{R}^2) \) for all \( s, t \) in \( \mathbb{R} \). Hence \( G \) is a null set or \( G = \mathbb{R}^2 \), and we have

\[
\text{ran} \left( \lim_{\lambda \to +\infty} E_\lambda \right) = \text{ran} \left( \lim_{\mu \to +\infty} F_\mu \right) = \bigcup_{\lambda, \mu} \alpha_{\lambda\beta}^* P_M = L^2(\mathbb{R}^2),
\]

\[
\text{ran} \left( \lim_{\lambda \to -\infty} E_\lambda \right) = \bigcap_{\lambda} \alpha_{\lambda\beta} P_M = \{0\},
\]

\[
\text{ran} \left( \lim_{\mu \to -\infty} F_\mu \right) = \bigcap_{\mu} \beta_{\mu} P_M = \{0\}.
\]

Therefore \( \{ E_\lambda \} \) and \( \{ F_\mu \} \) are the spectral families.

By virtue of Lemma 3.2, for any simple submodule of \( L^2(\mathbb{R}^2) \), there exists a spectral measure \( dE_{\lambda,\mu} = dE_{\lambda} dF_\mu \) on \( \mathbb{R}^2 \) and we have a two-parameter continuous unitary group \( \{ U_{s,t} \} \) on \( L^2(\mathbb{R}^2) \) as follows:

\[
U_{s,t} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{i(s\lambda + t\mu)} dE_{\lambda} dF_\mu = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{i(s\lambda + t\mu)} dE_{\lambda,\mu}.
\]
Definition 3.3 A family \( \{ A_{s,t} \} \) of functions on \( \mathbb{R}^2 \) which are individually measurable is said to be a cocycle of \( \mathbb{R}^2 \) if

(i) \( |A_{s,t}(x, y)| = 1 \) almost everywhere in \( x, y \), for each \( s, t \),

(ii) \( A_{s,t}f \) moves continuously in \( L^2(\mathbb{R}^2) \) as \( s \) and \( t \) varies, for each \( f \) in \( L^2(\mathbb{R}^2) \),

(iii) \( A_{s+u,t+v} = A_{s,t}U_{s,t} A_{u,v} \) almost everywhere, for each \( s, t, u \) and \( v \).

Example 3.1 (cf. [1]) In Lemma 5.3, we showed the following commutation relation:

\[ U_{s,0}T_{-s,0} \alpha \lambda \beta \mu = \alpha \lambda \beta \mu U_{s,0} T_{-s,0}. \]

Using the same argument with respect to the variable \( x_2 \), we have

\[ U_{s,t}T_{-s,-t} \alpha \lambda \beta \mu = \alpha \lambda \beta \mu U_{s,t} T_{-s,-t}. \]

Therefore \( U_{s,t}T_{-s,-t} \) is the multiplication operator by some unimodular function \( A_{s,t} \). We shall show \( \{ A_{s,t} \} \) is a cocycle of \( \mathbb{R}^2 \). Identifying bounded functions with multiplication operators, we have

\[
\begin{align*}
A_{s+u,t+v} & = U_{s+u,t+v} T_{-s-u,-t-v} \\
& = U_{s,u} U_{t,v} T_{-s-u,-t-v} \\
& = U_{s,u} A_{u,v} T_{-s,-t} \\
& = A_{s,t} U_{s,t} A_{u,v} T_{-s,-t}.
\end{align*}
\]

Hence

\[ A_{s+u,t+v}(x, y) = A_{s,t}(x, y) A_{u,v}(x - s, y - t). \]

Proposition 3.1 There exists a one-to-one correspondence between simple submodules of \( L^2(\mathbb{R}^2) \) and cocycles of \( \mathbb{R}^2 \).

Proof Suppose that \( \{ A_{s,t} \} \) is a cocycle of \( \mathbb{R}^2 \). Let \( U_{s,t} = A_{s,t} T_{s,t} \). Then \( \{ U_{s,t} \} \) is a two-parameter unitary group on \( L^2(\mathbb{R}^2) \). By Stone’s theorem for \( \mathbb{R}^2 \), there exists a unique spectral measure of \( L^2(\mathbb{R}^2) \) such that

\[ U_{s,t} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{i(s\lambda + t\mu)} \, dE_{\lambda, \mu}. \]

Let \( \mathcal{M} = \text{ran } E_{0,0} \). Then

\[
\begin{align*}
\int_{\mathbb{R}^2} e^{i(s\lambda + t\mu)} \, dE_{\lambda + \tau_1, \mu + \tau_2} &= e^{-i(s\tau_1 + t\tau_2)} \int_{\mathbb{R}^2} e^{i(s\lambda + t\mu)} \, dE_{\lambda + \tau_1, \mu + \tau_2} \\
& = e^{-i(s\tau_1 + t\tau_2)} \int_{\mathbb{R}^2} e^{i(s\lambda + t\mu)} \, dE_{\lambda, \mu} \\
& = \alpha_{\tau_1}^* \beta_{\tau_2}^* U_{s,t} \alpha_{\tau_1} \beta_{\tau_2} \\
& = \int_{\mathbb{R}^2} e^{i(s\lambda + t\mu)} \, d\left( \alpha_{\tau_1}^* \beta_{\tau_2}^* E_{\lambda, \mu} \alpha_{\tau_1} \beta_{\tau_2} \right)
\end{align*}
\]
Hence we have
\[ E_{\lambda + \tau_1, \mu + \tau_2} = \alpha_{\tau_1}^{*} \beta_{\tau_2}^{*} E_{\lambda, \mu} \alpha_{\tau_1} \beta_{\tau_2}. \]

Therefore \( \mathcal{M} \) is a submodule of \( L^2(\mathbb{R}^2) \).

Next, we shall show that \( \mathcal{M} \) satisfies the double commuting condition. It suffices to consider the case where \( \lambda \geq 0 \) and \( \mu \leq 0 \).

\[
P_{\mathcal{M}} \alpha_{\lambda} P_{\mathcal{M}} \beta_{\mu} P_{\mathcal{M}} = E_{0,0} \alpha_{\lambda} E_{0,0} \beta_{\mu} E_{0,0} = \alpha_{\lambda} E_{0,0} E_{0,0} = \alpha_{\lambda} E_{0,0} \beta_{\mu} = \alpha_{\lambda} E_{0,0} \beta_{\mu}.
\]

and
\[
P_{\mathcal{M}} \beta_{\mu} P_{\mathcal{M}} \alpha_{\lambda} P_{\mathcal{M}} = E_{0,0} \beta_{\mu} E_{0,0} \alpha_{\lambda} E_{0,0} = E_{0,0} E_{0,0} = E_{0,0} \alpha_{\lambda} \beta_{\mu} E_{0,0} = \alpha_{\lambda} \beta_{\mu} E_{0,0} = \alpha_{\lambda} E_{0,0} \beta_{\mu}.
\]

Therefore \( P_{\mathcal{M}} \alpha_{\lambda} P_{\mathcal{M}} \beta_{\mu} P_{\mathcal{M}} = P_{\mathcal{M}} \beta_{\mu} P_{\mathcal{M}} \alpha_{\lambda} P_{\mathcal{M}} \). This concludes the proof by Lemma 3.1.

**Example 3.2** (cf. [1]) Suppose that \( \mathcal{M} = qH^2(\mathbb{R}^2) \) for some unimodular function \( q \). Then its cocycle is \( \{ qT_{s,t}q^{-1} \} \).

A cocycle of the form \( A_{s,t} = qT_{s,t}q^{-1} \), for some unimodular function, is called a coboundary of \( \mathbb{R}^2 \).

**Corollary 3.1** Every cocycle of \( \mathbb{R}^2 \) is a coboundary of \( \mathbb{R}^2 \).

**Proof** By Theorem 2.1, for any simple submodule \( \mathcal{M} \) of \( L^2(\mathbb{R}^2) \), there is a unimodular function \( q \) such that \( \mathcal{M} = qH^2(\mathbb{R}^2) \). Hence the cocycle of \( \mathcal{M} \) is a coboundary.

**References**


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