The Existence of a Topolinear Isomorphism on an infinite dimensional Hilbert Space $H$ Corresponding to a Homeomorphism on its Projective Space $P(H)$

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Abstract

In this paper we prove a theorem which states the relationship between the topolinear isomorphisms on an infinite dimensional Hilbert Space $H$ and the Homeomorphisms on projective Space $P(H)$. This theorem is proved by E. Artin in the finite dimensional case.

Key words: Topolinear Isomorphism, Hilbert Space, Homeomorphism, Projective.
Introduction

The following $H$ is an infinite dimensional separable Hilbert Space and $P(H)$ is its projective space which is given a smooth structure as in [2]. We mean by $[x] \in P(H)$ the one dimensional vector subspace of $H$ generated by $x \in H = H^* - 0$.

$[x] + [y]$ means the two dimensional subspace generated by $x, y \in \hat{H}$, in fact $[x] \subset [x] + [y]$ is that there exists $a, b \in \hat{H}$ such that $z = ax + by$, and if $[z] \neq [x]$, There exists a unique $y \in \hat{H}$ such that $[z] = [x + dy]$. We quote some necessary statments from [2].

**Theorem 1.1** Let $S$ be a unit sphere in a normed space $B$ and $T : B \rightarrow B$ a linear bijective transformation, and $\hat{T}$ be the induced bijective transformation

$$\hat{T} : S \rightarrow S$$

defined by $\hat{T}(u) = \frac{T(u)}{||T(u)||}$ for $u \in S \subset B$.

This homeomorphism then $T$ is also homeomorphism.

Now we are ready to state the theorem which is the main goal of this paper

**Theorem 1.2** Let $f : P(H) \rightarrow P(H)$ be a homeomorphism such that

$$[x] \subset [y] + [z] \rightarrow f[x] \subset f[y] + f[z].$$

Then there exists a topolinear isomorphism $T : H \rightarrow H$ such that the induced transformation $P(H) \rightarrow P(H)$ agrees with $f$.

**Proof** the hypothesis implies that if $[x] \subset [y] + [z]$ then $f^{-1}[x] \subset f^{-1}[y] + f^{-1}[z]$ and by induction on $k$, we get that if $[z] \subset [z_1] + \cdots + [z_k]$ then $f[z] \subset f[z_1] + \cdots + f[z_k]$, and $f^{-1}[z] \subset f^{-1}[z_1] + \cdots + f^{-1}[z_k]$.

Let $\{x_i\}$ be a Hamel basis for $H$ where $i$ is an arbitrary element of a set $A$. It is clear that if $f[x_i] = [y_i]$ then $\{y_i\}$ is also a Hamel basis for $H$.

Now we choose an element of $A$ call it 1, then for any $i \neq 1$ the line

$$L_i = [x_i + x_i] \subset [x_1] + [x_i]$$

where $L_i$ is not coinide with $[x_i]$ or $[x_1]$, consequently

$$fL_i \subset [y_i] + [y_i]$$

and $fL_i$ is not coinide with $[y_i]$ or $[y_1]$. Then, for some unique $d_i \in \mathbb{R}$ we have

$$fL_i = [y_1 + d_i y_i].$$

by choosing a suitable $y_i$ we may assume that $d_i = 1$. Then

for $i \in A$, \hspace{2cm} f[x_i] = [y_i]$ \hspace{2cm}(1)

and for $i \neq 1$, \hspace{2cm} f[x_i] = [y_1 + y_i].$

Now we choose another index from $A$, call it 2. Then for $a \in \mathbb{R}$

$$L = [x_1 + ax_2] \subset [x_1] + [x_2] \text{ where } L \neq [x_2]$$

Therefore

$$fL \subset [y_1] + [y_2], \text{ where } fL \neq [y_2].$$

Then for a unique $a' \in \mathbb{R}$ we have

$$fL = [y_1 + a'y_2].$$
Chapter 1: Introduction

The following $H$ is an infinite dimensional separable Hilbert Space and $P(H)$ is its predual space which is given a smooth structure as in [2]. We mean by $[x] \in P(H)$ the $1$-dimensional vector subspace of $H$ generated by $x$. $[x] \subset [y] + [z]$ means the two dimensional subspace generated by $x, y \in H$. In fact $[z] \subset [x] + [y]$ as that there exists $a, b \in \mathbb{R}$ such that $z = ax + by$ and if $[z] \neq [x]$, there exists a unique $\xi \in \mathbb{R}$ such that $[z] = [x + d \xi y]$. We quote some necessary statements from [2].

**Theorem 1.1** Let $S$ be a unit sphere in a normed space $B$ and $T : B \to B$ a linear bijection, and $\hat{T}$ be the induced bijection transformation

$$\hat{T} : S \to S$$

defined by $\hat{T}(u) = \frac{T(u)}{\|T(u)\|}$ for $u \in S \subset B$. Then if $\hat{T}$ is a homeomorphism then $T$ is also homeomorphism.

Now we are ready to state the theorem which is the main goal of this paper.

**Theorem 1.2** Let $f : P(H) \to P(H)$ be a homeomorphism such that

$$[x] \subset [y] + [z] \implies f([x]) \subset f([y]) + f([z]).$$

Then there exists a topological isomorphism $T : P(H) \to H$ such that the induced transformation $f : P(H) \to P(H)$ agrees with $f$.

**Proof.** the hypothesis implies that if $[x] \subset [y] + [z]$ then $f^{-1}([x]) \subset f^{-1}([y]) + f^{-1}([z])$ and by induction on $k$, we get that if $[z] \subset [z_1] + \cdots + [z_k]$ then $f([z]) \subset f([z_1]) + \cdots + f([z_k])$, and $f^{-1}([z]) \subset f^{-1}([z_1]) + \cdots + f^{-1}([z_k])$.

Let $\{x_i\}$ be a Hamel basis for $H$ where $i$ is an arbitrary element of a set $A$. It is clear that if $f(x_i) = [y_i]$ then $\{y_i\}$ is also a Hamel basis for $H$.

Now we choose an element of $A$ call it 1, then for any $i \neq 1$ the line

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$$fL_i = [y_1 + d_i y_i].$$

by choosing a suitable $y_i$ we may assume that $d_i = 1$. Then

for $i \in A, \quad f[x_i] = [y_i]$ \quad (1)

and for $i \neq 1, f[x_1 + x_i] = [y_1 + y_i]$.

Now we choose another index from $A$, call it 2. Then for $a \in \mathbb{R}$

$$L = [x_1 + ax_2] \subset [x_1] + [x_2]$$

where $L \neq [x_2]$. Therefore

$$fL \subset [y_1] + [y_2], \quad \text{where } fL \neq [y_2].$$

Then for a unique $a' \in \mathbb{R}$ we have

$$fL = [y_1 + a' y_2].$$
Now we define
\[ \mu : R \rightarrow R \]
by \( \mu(a) = a' \) and we will show that \( \mu \) is the identity function on \( R \). Since
\[ [x_1 + ax_2] \neq [x_1 + bx_2] \text{ if } a \neq b \]
it follows that \( a' \neq b' \), then \( \mu \) is injective. We have also from (1) that
\[ 0' = 0 \text{ and } 1' = 1. \quad (2) \]

Now, we will show that for any \( i \in A \)
\[ f[x_1 + ax_i] = [y_1 + a'y_i] \]
For any fixed \( i \neq 1, 2 \) in \( A \) we have
\[ f[x_1 + ax_i] = [y_1 + by_i]. \]

On the other hand \( L = [ax_2 - ax_i] \subset [x_2] + [x_i] \)
with \( L \neq [x_i] \), and so \( fL \subset [y_2] + [y_i] \) with
\[ fL \neq [y_i]. \]
Consequently, \( fL = [y_2 + dy_1] \) for some unique \( d \). On the other hand,
\[ L \subset [x_1 + ax_2] + [x_1 + ax_i] \text{ with } L \neq [x_1 + ax_i]. \]

Then as before \( fL = \left[ (y_1 + a'y_i) + d'(y_1 + by_i) \right] \)
and it follows that \( d = -\frac{b}{a'} \). But
\[ L \subset [x_1 + x_2] + [x_1 + x_i] \text{ with } L \neq [x_1 + x_i] \]
and by (1)
\[ fL \subset [y_1 + y_2] + [y_1 + y_i] \text{ with } fL \neq [y_1 + y_i]. \]

Then for some unique \( h \) we have \( fL = [y_1 + y_2 + h(y_1 + y_i)] \), consequently \( d = -1 \) and \( b = a' \),
then for all \( i \in A \) and \( a \in R \) we have
\[ f[x_1 + ax_i] = [y_1 + a' y_i]. \quad (3) \]

Now we are going to prove that \( \mu \) is surjective. Choose a finite number of \( n \) vectors of \( \{x\} \) including \( x_1 \) and \( x_2 \) say \( x_1, x_2, \ldots, x_n \). Then induction we have
\[ f[x_1 + a_2x_2 + \cdots + a_n x_n] = [y_1 + a_2'y_2 + \cdots + a'_n y_n] \]
and it follows that
\[ f[a_2x_2 + \cdots + a_n x_n] = [a_2'y_2 + \cdots + a'_n y_n]. \] (4)


Let \( L = [y_1 + by_2] \) be a point of \( P(H) \), since \( \mu \) is bijective, then there exists some \( v \in H \) such that \( L = f[v] \), then \( v \) can be written as a linear combination of \( x_j \) including \( x_1, x_2 \). For the purpose we can use the above set \( x_1, x_2, \ldots, x_{n-1} \), then
\[ v = \alpha_1 x_1 + \alpha_2 x_2 + \cdots + \alpha_n x_n. \]

By (5) we have \( \alpha_1 \neq 0 \) and consequently,
\[ L = f[x_1 + \beta_2x_2 + \cdots + \beta_n x_n] \text{ with } \beta_j = \frac{\alpha_j}{\alpha_1}. \]
Then by (4) \( \beta_2' = b \) and consequently \( \mu \) is surjective.

To show that \( \mu(a + b) = \mu(a) + \mu(b) \) we consider the line \( L = [x_1 + (a+b)x_2 + x_3] \). Then by (2) and (3) we have
\[ fL = [y_1 + (a+b)y_2 + y_3] \]
but
\[ L \subset [x_1 + ax_2] + [bx_2 + x_3] \text{ and } L \neq [bx_2 + x_3]. \]

By (4) and (5)
\[ fL \subset [y_1 + a'y_2] + [0 + y_3] \text{ with } 0 \neq b. \]

References


