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COINCIDENCE POINT THEOREMS IN PSEUDOCOMPACT TICHONOV SPACES

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Abstract: In this paper, some coincidence point theorems for a pair of contractive type mappings and two pairs of expansive type mappings in pseudocompact Tichonov spaces are established. The results presented in this paper generalize the corresponding results of Harinath [1], Jain and Dixit [2] and Liu [6].

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1. Introduction

A topological space X is said to be pseudocompact if and only if each real valued continuous function on X is bounded. By Tichonov space we mean a completely regular Hausdorff space. It may be noted that every compact space

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is pseudocompact. If X is an arbitrary Tichonov space, then X is pseudocompact if and only if each real valued continuous function over X is bound and attains its bounds. The fixed point theorems for contractive mappings in pseudocompact Tichonov spaces were first established by Harinath [1]. Afterwards Jain and Dixit [2], [3], Liu [4], [6] and Rao [9] and others established a few fixed point theorems for several classes of contractive type mappings in pseudocompact Tichonov spaces. Liu [5] and Liu and Zhang [9] studied the existence of coincidence points for some pairs of contractive type mappings in pseudocompact Tichonov spaces.

The purpose of this paper is to establish the existence of coincidence point for some pairs of nonlinear mappings in pseudocompact Tichonov spaces. In Section 2, we prove coincidence point theorems for a pair of contractive type mappings. In Section 3, we obtain coincidence point theorems for two pairs of expansive type mappings. The results presented in this paper generalize the corresponding results of Harinath [1], Jain and Dixit [2] and Liu [6].

2. Coincidence Point Theorems of a Pair of Contractive Type Mappings

Theorem 2.1. *Let X be a pseudocompact Tichonov space and F denote a nonnegative real valued function on $X \times X$ and $F(x,y) = 0$ if and only if $x = y$. Suppose that f and g are self mappings on X such that $f(X) \subseteq g(X)$ and $a(x) = F(fx, gx)$ is continuous at each $x \in X$ and*

$$\begin{aligned} &F(fx, fy) \\ &\quad < \max\Big\{F(fx,gx), F(fy,gy), F(gx,gy), \frac{F(fx,gx)F(fy,gy)}{F(gx,gy)}, \\ &\quad \frac{F(fx,gy)F(gx,fy)}{F(gx,gy)}, \frac{[F(fx,gx)]^2}{F(fx,fy)}, \frac{[F(fy,gy)]^2}{F(fx,fy)}, \frac{[F(gx,gy)]^2}{F(fx,fy)}, \\ &\qquad \frac{F(fx,gy)F(gx,fy)}{F(fx,fy)}, \min\Big\{F(fx,gy), F(gx,fy), \\ &\qquad\qquad \frac{F(fx,gx)F(fx,gy)}{F(gx,gy)}, \frac{F(fx,gx)F(gx,fy)}{F(gx,gy)}\Big\}\Big\}, \end{aligned} \tag{2.1}$$

for all $x, y \in X$ with $fx \neq fy$ and $gx \neq gy$. Then f and g have a coincidence point in X. Moreover, if f and g commute at coincidence points, then f and g have a unique common fixed point in X.

Proof. Note that X is a pseudocompact Tichonov space and $a(x)$ is continuous on X. Consequently there exists a point $v \in X$ such that $a(v) = \inf\{a(x) : x \in X\}$. Since $f(X) \subseteq g(X)$, it follow that there exists $u \in X$ satisfying $fv = gu$. Suppose that f and g have no coincidence point. It follows that $fu \neq fv$ and $gu \neq gv$. Using (2.1), we deduce that

$$\begin{aligned}
&F(fu, fv)\\
&\quad < \max\Big\{F(fu, gu), F(fv, gv), F(gu, gv), \frac{F(fu, gu)F(fv, gv)}{F(gu, gv)},\\
&\quad \frac{F(fu, gv)F(gu, fv)}{F(gu, gv)}, \frac{[F(fu, gu)]^2}{F(fu, fv)}, \frac{[F(fv, gv)]^2}{F(fu, fv)}, \frac{[F(gu, gv)]^2}{F(fu, fv)},\\
&\qquad \frac{F(fu, gv)F(gu, fv)}{F(fu, fv)}, \min\Big\{F(fu, gv), F(gu, fv),\\
&\qquad \frac{F(fu, gu)F(fu, gv)}{F(gu, gv)}, \frac{F(fu, gu)F(gu, fv)}{F(gu, gv)}\Big\}\Big\}\\
&\quad = \max\Big\{F(fu, gu), F(fv, gv), \frac{[F(fv, gv)]^2}{F(fu, fv)}\Big\} = \max\Big\{a(v), \frac{[a(v)]^2}{a(u)}\Big\},
\end{aligned}$$

which means that $a(v) \leq a(u) < a(v)$. This is a contradiction. Hence f and g have a coincidence point. Consequently, $a(v) = 0$, that is, $fv = gv$. Moreover, if f and g commute at coincidence points, then

$$ffv = fgv = gfv = ggv. \tag{2.2}$$

Put $z = fv$. Now we show that is a common fixed point of f and g. Suppose that $fz \neq z$. According to (2.1) and (2.2), we have

$$\begin{aligned}
&F(fz, z) = F(ffv, fv)\\
&\quad < \max\Big\{F(ffv, gfv), F(fv, gv), F(gfv, gv), \frac{F(ffv, gfv)F(fv, gv)}{F(gfv, gv)},\\
&\quad \frac{F(ffv, gv)F(gfv, fv)}{F(gfv, gv)}, \frac{[F(ffv, gfv)]^2}{F(ffv, fv)}, \frac{[F(fv, gv)]^2}{F(ffv, fv)}, \frac{[F(gfv, gv)]^2}{F(ffv, fv)},\\
&\qquad \frac{F(ffv, gv)F(gfv, fv)}{F(ffv, fv)}, \min\Big\{F(ffv, gv), F(gfv, fv),\\
&\qquad \frac{F(ffv, gfv)F(ffv, gv)}{F(gfv, gv)}, \frac{F(ffv, gfv)F(gfv, fv)}{F(gfv, gv)}\Big\}\Big\}\\
&\qquad\qquad = F(gfv, gv) = F(fz, z),
\end{aligned}$$

which is a contradiction. Hence $z = fz = gz$. That is, z is a common fixed point of f and g.

To prove uniqueness, if possible suppose that w is another common fixed point of f and g with $w \neq z$. It follows from (2.1) that

$$\begin{aligned}
F(w,z) &= F(fw,fz) \\
&< \max\Big\{F(fw,gw), F(fz,gz), F(gw,gz), \frac{F(fw,gw)F(fz,gz)}{F(gw,gz)}, \\
&\quad \frac{F(fw,gz)F(gw,fz)}{F(gw,gz)}, \frac{[F(fw,gw)]^2}{F(fw,fz)}, \frac{[F(fz,gz)]^2}{F(fw,fz)}, \\
&\quad \frac{[F(gw,gz)]^2}{F(fwfz)}, \frac{F(fw,gz)F(gw,fz)}{F(fw,fz)}, \min\Big\{F(fw,gz), \\
&\quad F(gw,fz), \frac{F(fw,gw)F(fw,gz)}{F(gw,gz)}, \frac{F(fw,gw)F(gw,fz)}{F(gw,gz)}\Big\}\Big\} = F(w,z)\,,
\end{aligned}$$

which is a contradiction. Hence z is the only common fixed point of f and g. This completes the proof. □

In case g is the identity mapping on X, then Theorem 2.1 reduces to the following corollary.

Corollary 2.1. *Let X be a pseudocompact Tichonov space and F denote a nonnegative real valued function on $X \times X$ and $F(x,y) = 0$ if and only if $x = y$. Assume that $f : X \to X$ is a mapping such that $a(x) = F(fx,x)$ is continuous at each $x \in X$ and*

$$\begin{aligned}
F(fx,fy) &< \max\Big\{F(fx,x), F(fy,y), F(x,y), \frac{F(fx,x)F(fy,y)}{F(x,y)}, \\
&\quad \frac{F(fx,y)F(x,fy)}{F(x,y)}, \frac{[F(fx,x)]^2}{F(fx,fy)}, \frac{[F(fy,y)]^2}{F(fx,fy)}, \frac{[F(x,y)]^2}{F(fx,fy)}, \\
&\quad \frac{F(fx,y)F(x,fy)}{F(fx,fy)}, \min\Big\{F(fx,y), F(x,fy), \\
&\quad \frac{F(fx,x)F(fx,y)}{F(x,y)}, \frac{F(fx,x)F(x,fy)}{F(x,y)}\Big\}\Big\}, \qquad (2.3)
\end{aligned}$$

for all $x, y \in X$ with $fx \neq fy$. Then f has a unique fixed point in X.

Remark 2.1. Theorem 1 of Harinath [1], Theorem 2 of Jain and Dixit [2] and Theorem 1 of Liu [6] are special cases of Theorem 2.1 and Corollary 2.1. The following simple example shows that Theorem 2.1 extends properly the results of Harinath [1], Jain and Dixit [2] and Liu [6].

Example 2.1. Let $X = \{0, 1, 2\}$ and define $F : X \times X \to [0, +\infty)$ and $f, g : X \to X$ by $F(x, x) = 0$ and $F(x, y) = F(y, x)$ for all $x, y \in X$ and

$$F(0,1) = 1, \quad F(0,2) = F(1,2) = 2,$$
$$f0 = 0, \quad f1 = f2 = 1, \quad g0 = 2, \quad g1 = 0, \quad g2 = 1.$$

Note that $fx \neq fy$ and $gx \neq gy$ mean that $(x, y) \in \{(0, 1), (1, 0), (0, 2), (2, 0)\}$ and

$$F(fx, fy) = F(0, 1) = 1 < 2 = F(gx, gy).$$

It is clear that the conditions of Theorem 2.1 are fulfilled and that 2 is a coincidence point of f and g. But we cannot use Theorem 1 of Harinath [1], Theorem 2 of Jain and Dixit [2] and Theorem 1of Liu [6] to show the existence of fixed points of f since

$$F(fx, fy) < \max\Big\{F(fx, x), F(fy, y), F(x, y), \frac{F(fx, x)F(fy, y)}{F(x, y)}, \frac{F(fx, y), F(x, fy)}{F(x, y)}, \frac{F(fx, y)F(x, fy)}{F(fx, fy)}, \frac{[F(fx, y)]^2}{F(fx, fy)}, \frac{[F(fy, y)]^2}{F(fx, fy)}, \frac{[F(x, y)]^2}{F(fx, fy)}\Big\}$$

does not hold for $x = 0$ and $y = 1$.

3. Coincidence Point Theorems for Two Pairs of Expansive Type Mappings

Theorem 3.1. *Let X be a pseudocompact Tichonov space and F denote a nonnegative real valued function on $X \times X$ and $F(x, y) = 0$ if and only if $x = y$. Assume that f, g, s and t are four self mappings on X satisfying*

(a) $f(X) \subseteq t(X)$, $g(X) \subseteq s(X)$,

$$F(fx, gy) > \min\Big\{F(ty, sx), F(fx, sx), F(ty, gy), \frac{F(fx, sx)F(ty, gy)}{F(ty, sx)}, \frac{[F(ty, sx)]^2}{F(fx, gy)}, \frac{[F(fx, sx)]^2}{F(fx, gy)}, \frac{[F(ty, gy)]^2}{F(fx, gy)}\Big\}, \tag{3.1}$$

for all $x, y \in X$ with $fx \neq gy$ and $ty \neq sx$, and one of the following conditions:

(b) $a(x) = F(fx, sx)$ *is continuous at each* $x \in X$,

(c) $b(x) = F(tx, gx)$ *is continuous at each* $x \in X$.

Then either f *and* s *or* g *and* t *have a coincidence point in* X.

Proof. Suppose that (c) holds. Since X is a pseudocompact Tichonov space, it follows that there exists x_0 in X such that $b(x_0) = \sup\{b(x) : x \in X\}$. By (a), there exists x_1 and x_2 in X such that $gx_0 = sx_1$ and $fx_1 = tx_2$. Suppose that neither f and s nor g and t have coincidence points. Then $fx_1 \neq gx_2$ and $tx_2 \neq sx_1$. In view of (3.1), we know that

$$\begin{aligned} b(x_2) &= F(fx_1, gx_2) \\ &> \min\Big\{F(tx_2, sx_1), F(fx_1, sx_1), F(tx_2, gx_2), \frac{F(fx_1, sx_1)F(tx_2, gx_2)}{F(tx_2, sx_1)}, \\ &\qquad \frac{[F(tx_2, sx_1)]^2}{F(fx_1, gx_2)}, \frac{[F(fx_1, sx_1)]^2}{F(fx_1, gx_2)}, \frac{[F(tx_2, gx_2)]^2}{F(fx_1, gx_2)}\Big\} \\ &= \min\Big\{F(fx_1, sx_1), F(fx_1, gx_2), \frac{[F(fx_1, sx_1)]^2}{F(fx_1, gx_2)}\Big\} \\ &= \min\Big\{F(fx_1, sx_1), \frac{[F(fx_1, sx_1)]^2}{F(fx_1, gx_2)}\Big\}, \end{aligned}$$

so that $b(x_2) > F(fx_1, sx_1)$. Using (3.1), we infer that

$$\begin{aligned} F(fx_1, sx_1) &= F(fx_1, gx_0) \\ &> \min\Big\{F(tx_0, sx_1), F(fx_1, sx_1), F(tx_0, gx_0), \\ &\qquad \frac{F(fx_1, sx_1)F(tx_0, gx_0)}{F(tx_0, sx_1)}, \frac{[F(tx_0, sx_1)]^2}{F(fx_1, gx_0)}, \frac{[F(fx_1, sx_1)]^2}{F(fx_1, gx_0)}, \frac{[F(tx_0, gx_0)]^2}{F(fx_1, gx_0)}\Big\} \\ &= \min\Big\{F(tx_0, gx_0), F(fx_1, gx_0), \frac{[F(tx_0, gx_0)]^2}{F(fx_1, gx_0)}\Big\} \\ &= \min\Big\{F(tx_0, sx_0), \frac{[F(tx_0, gx_0)]^2}{F(fx_1, gx_0)}\Big\}, \end{aligned}$$

which means that

$$b(x_2) > F(fx_1, sx_1) > F(tx_0, gx_0) = b(x_0),$$

which is a contradiction. Hence either f and s or g and t have a coincidence point. Similarly we can prove that the theorem when (b) holds. This completes the proof. □

Remark 3.1. The example below shows that the coincidence points of f and s or g and t in Theorem 3.1 may not be unique.

Example 3.1. Let $X = \{1, 2, 3, 4\}$ with F defined by $F(x, x) = 0$ and $F(x, y) = F(y, x)$ for all $x, y \in X$ and

$$F(1,2) = F(1,4) = F(3,4) = 1,\ F(2,3) = 2,\ F(1,3) = 1.2,\ F(2,4) = 1.5.$$

Then X is a pseudocompact Tichonov space. Define f, g, s and $t : X \to X$ by

$$\begin{aligned} &f1 = f2 = f4 = 1,\ f3 = 4,\ g1 = g2 = 4,\ g3 = g4 = 1,\\ &s1 = 3,\ s2 = 1,\ s3 = 4,\ s4 = 2,\ t1 = 4,\ t2 = t4 = 2,\ t3 = 1. \end{aligned}$$

It is easy to see that the conditions of Theorem 3.1 are satisfied. However, 2 and 3 are coincidence points of f and s, and 1 and 3 are coincidence points of g and t.

Theorem 3.2. *Let X be a pseudocompact Tichonov space and F denote a nonnegative real valued function on $X \times X$ and $F(x, y) = 0$ if and only if $x = y$. Assume that f is a self mapping on X such that $a(x) = F(fx, x)$ is continuous at each $x \in X$ and*

$$\begin{aligned} F(fx, fy) > \min\Big\{&F(x,y), \frac{F(fx,x)F(fy,y)}{F(x,y)}, \frac{[F(fy,y)]^2}{F(x,y)},\\ &\max\Big\{\frac{F(fx,fy)F(fy,y)}{F(x,y)}, \frac{F(fy,x)F(fx,y)}{F(x,y)},\\ &\frac{F(fx,x)F(fy,x)}{F(x,y)}, \frac{F(fx,fy)F(fy,x)}{F(x,y)}, \frac{[F(fy,x)]^2}{F(x,y)}\Big\},\\ &\frac{[F(x,y)]^2}{F(fx,fy)}, \frac{[F(fx,x)]^2}{F(fx,fy)}, \frac{[F(fy,y)]^2}{F(fx,fy)}, \frac{F(fx,x)F(x,y)}{F(fx,fy)},\\ &\frac{F(fx,x)F(fy,y)}{F(fx,fy)}, \frac{F(fy,y)F(x,y)}{F(fx,fy)}\Big\}, \end{aligned} \tag{3.2}$$

for all $x, y \in X$ with $fx \neq fy$. Then f has a fixed point in X.

Proof. Since X is a pseudocompact Tichonov space and $a(x)$ is continuous at each $x \in X$, it follows that there exists a point x_0 such that $a(x_0) = \sup\{a(x) : x \in X\}$. Suppose that $f^2x_0 \neq fx_0$. Then $fx_0 \neq x_0$. In view of (3.2), we arrive at

$$F(f^2x_0, fx_0)$$

$$
\begin{aligned}
&> \min\Big\{F(fx_0,x_0), \frac{F(f^2x_0,fx_0)F(fx_0,x_0)}{F(fx_0,x_0)}, \frac{[F(fx_0,x_0)]^2}{F(fx_0,x_0)},\\
&\max\Big\{\frac{F(f^2x_0,fx_0)F(fx_0,x_0)}{F(fx_0,x_0)}, \frac{F(fx_0,fx_0)F(f^2x_0,x_0)}{F(fx_0,x_0)},\\
&\frac{F(f^2x_0,fx_0)F(fx_0,fx_0)}{F(fx_0,x_0)}, \frac{F(f^2x_0,fx_0)F(fx_0,fx_0)}{F(fx_0,x_0)},\\
&\frac{[F(fx_0,fx_0)]^2}{F(fx_0,x_0)}\Big\}, \frac{[F(fx_0,x_0)]^2}{F(f^2x_0,fx_0)}, \frac{[F(f^2x_0,fx_0)]^2}{F(f^2x_0,fx_0)},\\
&\frac{[F(fx_0,x_0)]^2}{F(f^2x_0,fx_0)}, \frac{F(f^2x_0,fx_0)F(fx_0,x_0)}{F(f^2x_0,fx_0)},\\
&\frac{F(f^2x_0,fx_0)F(fx_0,x_0)}{F(f^2x_0,fx_0)}, \frac{F(fx_0,x_0)F(fx_0,x_0)}{F(f^2x_0,fx_0)}\Big\}\\
&= \min\Big\{F(fx_0,x_0), F(f^2x_0,fx_0), \frac{[F(fx_0,x_0)]^2}{F(f^2x_0,fx_0)}\Big\}\\
&= \min\Big\{F(fx_0,x_0), \frac{[F(fx_0,x_0)]^2}{F(f^2x_0,fx_0)}\Big\},
\end{aligned}
$$

which implies that $a(fx_0) > a(x_0)$ This is a contradiction. Hence $f^2x_0 = fx_0$. This completes the proof. □

Theorem 3.3. *Let X be a pseudocompact Tichonov space and F denote a nonnegative real valued function on $X \times X$ and $F(x,y) = 0$ if and only if $x = y$. Assume that f is a self mapping on X such that $a(x) = F(fx,x)$ is continuous at each $x \in X$ and*

$$
\begin{aligned}
&\max\{F(fx,fy), \min\{F(fx,y), F(fy,x)\}\}\\
&> \min\Big\{F(x,y), \frac{F(fx,x)F(fy,y)}{F(x,y)}, \frac{[F(fy,y)]^2}{F(x,y)}, \frac{[F(x,y)]^2}{F(fx,fy)}, \frac{[F(fx,x)]^2}{F(fx,fy)},\\
&\frac{[F(fy,y)]^2}{F(fx,fy)}, \frac{F(fx,x)F(x,y)}{F(fx,fy)}, \frac{F(fx,x)F(fy,y)}{F(fx,fy)}, \frac{F(fy,y)F(x,y)}{F(fx,fy)}\Big\}\\
&- \min\Big\{\frac{F(fx,fy)F(fy,y)}{F(x,y)}, \frac{F(fx,x)F(fy,x)}{F(x,y)}, \frac{F(fy,x)F(fx,y)}{F(x,y)},\\
&\frac{F(fx,fy)F(fy,x)}{F(x,y)}, \frac{[F(fy,x)]^2}{F(x,y)}\Big\}, \quad (3.3)
\end{aligned}
$$

for all $x, y \in X$ with $fx \neq fy$. Then f has a fixed point in X.

Proof. Note that X is a pseudocompact Tichonov space and $a(x)$ is continuous at each $x \in X$. Thus there exists a point $x_0 \in X$ such that $a(x_0) = \sup\{a(x) : x \in X\}$. If $f^2x_0 \neq fx_0$, then $fx_0 \neq x_0$. By (3.3), we conclude that

$$\begin{aligned}
&\min\Big\{F(fx_0,x_0), \frac{F(f^2x_0,fx_0)F(fx_0,x_0)}{F(fx_0,x_0)}, \frac{[F(fx_0,x_0)]^2}{F(fx_0,x_0)},\\
&\frac{[F(fx_0,x_0)]^2}{F(f^2x_0,fx_0)}, \frac{[F(f^2x_0,fx_0)]^2}{F(f^2x_0,fx_0)}, \frac{[F(fx_0,x_0)]^2}{F(f^2x_0,fx_0)}, \frac{F(f^2x_0,fx_0)F(fx_0,x_0)}{F(f^2x_0,fx_0)},\\
&\frac{F(f^2x_0,fx_0)F(fx_0,x_0)}{F(f^2x_0,fx_0)}, \frac{F(fx_0,x_0)F(fx_0,x_0)}{F(f^2x_0,fx_0)}\Big\}\\
&-\min\Big\{\frac{F(f^2x_0,fx_0)F(fx_0,x_0)}{F(fx_0,x_0)}, \frac{F(f^2x_0,fx_0)F(fx_0,fx_0)}{F(fx_0,x_0)},\\
&\frac{F(fx_0,fx_0)F(f^2x_0,x_0)}{F(fx_0,x_0)}, \frac{F(f^2x_0,fx_0)F(fx_0,fx_0)}{F(fx_0,x_0)}, \frac{[F(fx_0,fx_0)]^2}{F(fx_0,x_0)}\Big\}\\
&= \min\Big\{F(fx_0,x_0), F(f^2x_0,fx_0), \frac{[F(fx_0,x_0)]^2}{F(f^2x_0,fx_0)}\Big\}\\
&< \max\{F(f^2x_0,fx_0), \min\{F(f^2x_0,x_0), F(fx_0,fx_0)\}\}\\
&= F(f^2x_0,fx_0),
\end{aligned}$$

which means that

$$a(fx_0) > a(x_0) \geq a(fx_0),$$

which is impossible. Consequently $f^2x_0 = fx_0$. This completes the proof. □

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