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EXTENSION OF FIXED POINT THEOREMS TYPE T-ZAMFIRESCU MAPPING IN CONE METRIC SPACE

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Abstract: The objective of this paper is to obtain sufficient conditions for the existence of fixed point of T-Zamfirescu in complete cone metric spaces and we prove fixed point theorem for an extended Kannan and Chatterjea type T-contraction mapping in a cone metric space. Our results generalize recent results existing in the literature of T-Zamfirescu mappings in cone metric space.

Keywords and Phrases: Cone Metric Space, T-Zamfirescu mapping, Cone normed space.

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1. Introduction

In [4], Huang and Zhang introduced the concept of cone metric space as a generalization of metric space, in which they replace the set of real numbers with a real Banach space. After that, many others [1, 2, 5, 6, 7, 12] proved numerous fixed point theorems for contractive type mappings on a cone metric space. Morales and Rojas [10], [9], [11] have extended the concept of T-contraction mappings to cone metric space by proving fixed point theorems for T-Kannan, T-Zamfirescu, T-weakly contraction mappings. The purpose of this paper is to prove fixed point theorem for an extended Kannan and Chatterjea T-Zamfirescu type mapping in a cone metric space. Our results pull out and generalized fixed point theorems of [8].

2. Preliminaries and Definition

Definition 2.1. *Let $(E, \|\cdot\|)$ be a real Banach space and R be set of real number. A subset $P \subseteq E$ is said to be a cone if and only if*
(i) P *is closed, nonempty and* $P \neq \{0\}$
(ii) $a, b \in R,\ a, b \geq 0,\ x, y \in P$ *implies* $ax + by \in P$
(iii) $P \cap (-P) = \{0\}$

For a given cone P subset of E, we define a partial ordering $\leq$ with respect to P by $x \leq y$ if and only if $y - x \in P$. We shall write $x < y$ to indicate that $x \leq y$ but $x \neq y$ while $x \ll y$ will stand for $y - x \in int\, P$ where $int\, P$ denotes interior of ***P*** *and is assumed to be nonempty.*

Definition 2.2. [4] *Let X be a nonempty set. Suppose that the mapping $d : X \times X \to E$ satisfies*
(i) $0 \leq d(x, y)$ *for every* $x, y \in X,\ d(x, y) = 0$ *if and only if* $x = y$.
(ii) $d(x, y) = d(y, x)$ *for every* $x, y \in X$.
(iii) $d(x, y) \leq d(x, z) + d(z, y)$ *for every* $x, y, z \in X$.
Then d is a cone metric on X and (X, d) is a cone metric space.

Example 2.3. [3] Let $E = R^n,\ P = \big\{(x, y) \in E : x, y \geq 0\big\} \subset R^2,\ X = R$ and $d : X \times X \to E$ such that $d(x, y) = \big(|x - y|, \alpha|x - y|\big)$, where $\alpha \geq 0$ is a constant. Then (X, d) is a cone metric space.

Definition 2.4. *Let E be a Banach space and $P \subset E$ a cone. The cone P is called normal if there is a number $K > 0$ such that for all $x, y \in E$,*

$$0 \leq x \leq y \ \ Implies \ \ \|x\| \leq K \|y\|.$$

The least positive number satisfying the above inequality is called the normal constant of P.

Then $\|\cdot\|$ is called a norm on X, and $(X, \|\cdot\|)$ is called a cone normed space. Clearly each cone normed space is a cone metric space with metric defined by $d(x, y) = \|x - y\|$.

Definition 2.5. [3] *Let (X, d) be a cone metric space, $x \in X$ and $\{x_n\}$ a sequence in X. Then*
(i) $\{x_n\}$ *converges to x if for every $c \in E$ with $0 \ll c$ there is a natural number N such that $d(x_n, x) \leq c$ for all $n \geq N$*
We shall denote it by $\lim_{n\to\infty} x_n = x$ *or* $x_n \to x$.
(ii) $\{x_n\}$ *is a Cauchy sequence, if for every $c \in E$ with $0 \ll c$ there is a natural number N such that*

$$d(x_n, x) \leq c \ \ for\ all \ \ n, m \geq N.$$

(iii) (X, d) *is a complete cone metric space if every Cauchy sequence is convergent in* X.

Definition 2.6. *Let* $(X, \|\cdot\|)$ *be a cone normed space,* $x \in X$ *and* $\{x_n\}$ *a sequence in* X. *Then*
(i) $\{x_n\}$ *converges to* x *if for every* $c \in E$ *with* $0 \ll c$ *there is a natural number* N *such that* $\|x_n - x\| \leq c$ *for all* $n \geq N$
We shall denote it by $\lim_{n\to\infty} x_n = x$ *or* $x_n \to x$.
(ii) $\{x_n\}$ *is a Cauchy sequence, if for every* $c \in E$ *with* $0 \ll c$ *there is a natural number* N *such that*

$$\|x_n - x_m\| \leq c \ \text{ for all } \ n, m \geq N.$$

(iii) $(X, \|\cdot\|)$ *is a complete cone normed space if every Cauchy sequence is convergent. A complete cone normed space is called a Cone Banach space.*

Lemma 2.7. [3] *Let* (X, d) *be a cone normed space.* P *be a normal cone with constant* K. *Let* $\{x_n\}, \{y_n\}$ *be a sequence in* X *and* $x, y \in X$. *Then*
(i) $\{x_n\}$ *converges to* x *if and only if* $\lim_{n\to\infty} d(x_n, x) = 0$.
(ii) If $\{x_n\}$ *converges to* x *and* $\{x_n\}$ *converges to* y *then* $x = y$.
(iii) If $\{x_n\}$ *is a Cauchy sequence if and only* $\lim_{n,m\to\infty} d(x_n, x_m) = 0$.
(iv) If the sequence $\{x_n\}$ *converges to* x *and* $\{y_n\}$ *converges to* y *then*

$$d(x_n, y_n) \to d(x, y).$$

Definition 2.8. *Let* (X, d) *be a cone metric space,* P *be a normal cone with normal constant* K *Let* $T : X \to X$. *Then*
(i) T *is said to be continuous,*

$$\text{if } \lim_{n\to\infty} x_n = x \ \text{ implies that } \ \lim_{n\to\infty} Tx_n = Tx \ \text{ for every } \ \{x_n\} \ \text{ in } \ X.$$

(ii) T *is said to be sequentially convergent if we have, for every sequence* $\{y_n\}$, *if* $T(y_n)$ *is convergent, then* $\{y_n\}$ *also is convergent.*
Now, following the ideas of T. Zamfirescu, we introduce the notion of T-Zamfirescu mappings.

Definition 2.9. [14] *Let* (X, d) *be a cone metric space and* $T, S : X \to X$ *two mappings.* S *is called a* T*-Zamfirescu mapping, (TZ-mapping), if and only if, there are real numbers,* $0 \leq a < 1$, $0 \leq b$, $c < 1/2$ *such that for all* $x, y \in X$, *at least* *one of the next conditions are true:*

$$(TZ_1): \quad d(TSx, TSy) \leq ad(Tx, Ty).$$
$$(TZ_2): \quad d(TSx, TSy) \leq b\big[d(Tx, TSx) + d(Ty, TSy)\big].$$
$$(TZ_1): \quad d(TSx, TSy) \leq c\big[d(Tx, TSy) + d(Ty, TSx)\big].$$

Corollary 2.10. [13] *Let $a, b, c, u \in E$ the real Banach space*
(i) If $a \leq b$ and $b \ll c$ then $a \ll c$.
(ii) If $a \ll b$ and $b \ll c$ then $a \ll c$.
(iii) If $0 \leq u \ll c$ for each $c \in int\, P$, then $u = 0$.

3. Main Results

Lemma 3.1. *Let (X, d) be a cone metric space and $T, S : X \to X$ two mappings with*

$$d(TSx, TSy) \leq \alpha\Big[d(Tx, TSx) + d(Ty, TSy)\Big] + \beta d(Tx, Ty) \tag{3.1}$$

for all $x, y \in X$ where $0 \leq \alpha$ and $0 \leq \beta \leq 1$. Then S is a T-Zamfirescu mapping.
Proof. Let (X, d) be a cone metric space and $T, S : X \to X$ two mappings with

$$d(TSx, TSy) \leq \alpha\Big[d(Tx, TSx) + d(Ty, TSy)\Big] + \beta d(Tx, Ty)$$

for all $x, y \in X$. Where $0 \leq \alpha$ and $0 \leq \beta \leq 1$

$$\begin{aligned}
d(TSx, TSy) &\leq \alpha\Big[d(Tx, TSx) + d(Ty, TSy)\Big] + \beta d(Tx, Ty)\\
d(TSx, TSy) &\leq \alpha\Big[d(Tx, TSx) + d(Ty, TSy)\Big] + \beta\Big\{d(Tx, TSx)\\
&\qquad + d(TSx, TSy) + d(TSy, Ty)\Big\}\\
(1-\beta)d(TSx, TSy) &\leq (\alpha+\beta)\Big[d(Tx, TSx) + d(Ty, TSy)\Big]\\
d(TSx, TSy) &\leq \frac{(\alpha+\beta)}{(1-\beta)}\Big[d(Tx, TSx) + d(Ty, TSy)\Big]\\
d(TSx, TSy) &\leq b\Big[d(Tx, TSx) + d(Ty, TSy)\Big]\\
&\qquad\qquad \text{where } \ b = \frac{(\alpha+\beta)}{(1-\beta)} \geq 0.
\end{aligned}$$

Hence by definition of T-Zamfirescu, S is T-Zamfirescu mapping.

Theorem 3.2. *Let (X, d) be a complete cone metric space, P be normal cone with normal cone with normal constant K. Moreover, let $T : X \to X$ be a continuous and injective mapping and $S : X \to X$ a continuous mapping. If the mappings T and S satisfy*

$$d(TSx, TSy) \leq \alpha\Big[d(Tx, TSx) + d(Ty, TSy)\Big] + \beta d(Tx, Ty) \tag{3.2}$$

for all $x, y \in X$, where $0 \leq \alpha$ and $0 \leq \beta \leq 1$. Then S has a unique fixed point in X.

Proof. Let $x_0 \in X$ be arbitrary. Define a sequence $\{x_n\}$ in X such that $x_{n+1} = Sx_n$ for each $= 0, 1, 2, ..., \infty$.
We have

$$\begin{aligned}
d(TSx_n, TSx_{n-1}) &\leq \alpha\Big[d(Tx_n, TSx_n) + d(Tx_{n-1}, TSx_{n-1})\Big] \\
&\quad + \beta d(Tx_n, Tx_{n-1}) \\
d(Tx_{n+1}, Tx_n) &\leq \alpha\Big[d(Tx_n, Tx_{n+1}) + d(Tx_{n-1}, Tx_n)\Big] \\
&\quad + \beta d(Tx_{n-1}, Tx_n) \\
(1-\alpha)d(Tx_{n+1}, Tx_n) &\leq (\alpha + \beta)d(Tx_{n-1}, Tx_n). \\
d(Tx_{n+1}, Tx_n) &\leq \frac{(\alpha+\beta)}{(1-\alpha)} d(Tx_{n-1}, Tx_n).
\end{aligned}$$

Proceeding as above

$$d(Tx_{n+1}, Tx_n) \leq \frac{(\alpha+\beta)^n}{(1-\alpha)} d(Tx_0, Tx_1).$$

Next, to claim that $\{Tx_n\}$ is a Cauchy sequence. Consider $m, n \in N$ such that $m > n$

$$\begin{aligned}
d(Tx_n, Tx_m) &\leq d(Tx_n, Tx_{n+1}) + d(Tx_{n+1}, Tx_{n+2}) + \cdots + d(Tx_{m-1}, Tx_m) \\
d(Tx_n, Tx_m) &\leq \left[\frac{(\alpha+\beta)^n}{(1-\alpha)} + \frac{(\alpha+\beta)^{n+1}}{(1-\alpha)} + \cdots + \frac{(\alpha+\beta)^{m-1}}{(1-\alpha)}\right] d(Tx_0, Tx_1) \quad (3.3)
\end{aligned}$$

We take $\frac{\alpha+\beta}{1-\alpha} = k$, the inequality (3.3) implies that for all $m, n \in N$, $n > m$

$$d(Tx_n, Tx_m) \leq \frac{k^n}{1-k} d(Tx_0, Tx_1).$$

Since, P be normal cone, therefore

$$\|d(Tx_n, Tx_m)\| \leq \frac{k^n}{1-k} \|d(Tx_0, Tx_1)\| .$$

Further, since $k \in (0,1), k^n \to 0$ as $n \to \infty$.
Therefore $\|d(Tx_n, Tx_m)\| \to 0$ as $m, n \to \infty$.
Thus, $\{Tx_n\}$ is a Cauchy sequence in X. As X is a complete cone metric space, there exists $z \in X$ such that

$$\lim_{n\to\infty} Tx_n = z.$$

Since T is sub-sequentially convergent, $\{x_n\}$ has a convergent subsequence $\{x_m\}$ such that

$$\lim_{m\to\infty} Tx_m = u$$

Since, T is continuous implies that

$$\lim_{m\to\infty} Tx_m = Tu \tag{3.4}$$

By the uniqueness of the limit, $z = Tu$.
Since S is continuous,

$$\lim_{m\to\infty} Sx_m = Su$$

Again as T is continuous,

$$\lim_{m\to\infty} TSx_m = TSu$$

Therefore

$$\lim_{m\to\infty} TSx_{m+1} = TSu \tag{3.5}$$

Now consider,

$$\begin{aligned}
d(TSu,Tu) &\leq d(TSu,Tx_m) + d(Tx_m,Tu)\\
d(TSu,Tu) &\leq \alpha\Big[d(Tu,TSu) + d(Tx_{m-1},Tx_m)\Big] + \beta d(Tu,Tx_{m-1})\\
&\quad + d(Tx_m,Tu)\\
(1-\alpha)d(TSu,Tu) &\leq \alpha d(Tx_{m-1},Tx_m) + \beta d(Tu,Tx_{m-1}) + d(Tx_m,Tu)\\
d(TSu,Tu) &\leq \frac{\alpha}{1-\alpha}d(Tx_{m-1},Tx_m) + \frac{\beta}{1-\alpha}d(Tu,Tx_{m-1})\\
&\quad + \frac{1}{1-\alpha}d(Tx_m,Tu)\\
d(TSu,Tu) &\leq \frac{\alpha}{1-\alpha}d(Tx_{m-1},Tx_m) + \frac{\beta}{1-\alpha}\Big\{d(Tu,Tx_m)\\
&\quad + d(Tx_m,Tx_{m-1})\Big\} + \frac{1}{1-\alpha}d(Tx_m,Tu)\\
d(TSu,Tu) &\leq \frac{\alpha+\beta}{1-\alpha}d(Tx_{m-1},Tx_m) + \frac{\beta+1}{1-\alpha}d(Tu,Tx_m) \qquad (3.6)
\end{aligned}$$

Let $0 \ll c$ be arbitrary, By (3.4), we have

$$d(Tu,Tx_m) \ll \frac{c(1-\alpha)}{2(1+\beta)}$$

And by (3.5) we have

$$d(Tx_{m-1},Tx_m) \ll \frac{c(1-\alpha)}{2(\alpha+\beta)}$$

Then (3.6) becomes,

$$d(TSu,Tu) \ll c \ \text{ for each } c \in \operatorname{int} P$$

Now, Using Corollary (2.10-iii), it follows that $d(TSu,Tu) = 0$ which implies that $Tu = TSu$

Since T is one-to-one, Thus u is the fixed point of S.

We claim that, u is the fixed point of.

If w is another fixed point of S, then $w = Sw$

$$\begin{aligned}
d(Tu,Tw) &= d(TSu,TSw)\\
&\leq \alpha\Big(d(Tu,TSu) + d(Tw,TSw)\Big) + \beta d(Tu,Tw)\\
&\leq \beta d(Tu,Tw)
\end{aligned}$$

This is a contradiction. Hence $d(Tu, Tw) = 0 \Rightarrow Tu = Tw$. As T is injective, $u = w$. Therefore the fixed point of S is unique.

Theorem 3.3. *Let (X, d) be a complete cone metric space, P be normal cone with normal cone with normal constant K. Moreover, let $T : X \to X$ be a continuous and injective mapping and $S : X \to X$ a continuous mapping. If the mappings T and S satisfy*

$$d(TSx, TSy) \leq \alpha\Big[d(Ty, TSx) + d(Tx, TSy)\Big] + \beta d(Tx, Ty) \tag{3.7}$$

for all $x, y \in X$, where $\alpha > 0, \beta \geq 0, 2\alpha + \beta < 1$ then S has an unique fixed point in X.

Proof. Let $x_0 \in X$ be arbitrary. Define a sequence $\{x_n\}$ in X such that $x_{n+1} = Sx_n$ for each $= 0, 1, 2, ..., \infty$.

We have

$$\begin{aligned} d(TSx_n, TSx_{n-1}) &\leq \alpha\Big[d(Tx_{n-1}, TSx_n) + d(Tx_n, TSx_{n-1})\Big] \\ &\quad + \beta d(Tx_{n-1}, Tx_n) \\ d(Tx_{n+1}, Tx_n) &\leq \alpha\Big[d(Tx_{n-1}, Tx_{n+1}) + d(Tx_n, Tx_n)\Big] \\ &\quad + \beta d(Tx_{n-1}, Tx_n) \\ d(Tx_{n+1}, Tx_n) &\leq \alpha d(Tx_{n-1}, Tx_{n+1}) + \beta d(Tx_{n-1}, Tx_n) \\ d(Tx_{n+1}, Tx_n) &\leq \alpha\Big\{d(Tx_{n-1}, Tx_{n+1}) + d(Tx_n, Tx_{n+1})\Big\} \\ &\quad + \beta d(Tx_{n-1}, Tx_n) \\ (1-\alpha)d(Tx_{n+1}, Tx_n) &\leq (\alpha + \beta)d(Tx_{n-1}, Tx_n) \\ d(Tx_{n+1}, Tx_n) &\leq \frac{(\alpha+\beta)}{(1-\alpha)}d(Tx_{n-1}, Tx_n) \end{aligned}$$

Proceeding as above

$$d(Tx_{n+1}, Tx_n) \leq \frac{(\alpha+\beta)^n}{(1-\alpha)}d(Tx_0, Tx_1)$$

Next, to claim that $\{Tx_n\}$ is a Cauchy sequence. Consider $m, n \in N$ such that $m > n$

$$\begin{aligned} d(Tx_n, Tx_m) &\leq d(Tx_n, Tx_{n+1}) + d(Tx_{n+1}, Tx_{n+2}) + \cdots + d(Tx_{m-1}, Tx_m) \\ d(Tx_n, Tx_m) &\leq \left[\frac{(\alpha+\beta)^n}{(1-\alpha)} + \frac{(\alpha+\beta)^{n+1}}{(1-\alpha)} + \cdots + \frac{(\alpha+\beta)^{m-1}}{(1-\alpha)}\right]d(Tx_0, Tx_1) \end{aligned} \tag{3.8}$$

We take $\frac{\alpha+\beta}{1-\alpha}=k$,

$$d(Tx_n,Tx_m)\leq\left[k^n+k^{n+1}+\cdots+k^{m-1}\right]d(Tx_0,Tx_1)$$
$$d(Tx_n,Tx_m)\leq\frac{k^n}{1-k}d(Tx_0,Tx_1)$$

Since, P be normal cone, therefore

$$\|d(Tx_n,Tx_m)\|\leq\frac{k^n}{1-k}\,\|d(Tx_0,Tx_1)\|$$

Further, since $k\in(0,1), k^n\to 0$ as $n\to\infty$. Therefore $\|d(Tx_n,Tx_m)\|\to 0$ as $m,n\to\infty$
Thus, $\{Tx_n\}$ is a Cauchy sequence in X. As X is a complete cone metric space, there exists $z\in X$ such that

$$\lim_{n\to\infty}Tx_n=z$$

Since T is sub-sequentially convergent, $\{x_n\}$ has a convergent subsequence $\{x_m\}$ such that

$$\lim_{m\to\infty}Tx_m=u$$

Since, T is continuous implies that

$$\lim_{m\to\infty}Tx_m=Tu \tag{3.9}$$

By the uniqueness of the limit, $z=Tu$.
Since S is continuous,

$$\lim_{m\to\infty}Sx_m=Su$$

Again as T is continuous,

$$\lim_{m\to\infty}TSx_m=TSu$$

Therefore

$$\lim_{m\to\infty}TSx_{m+1}=TSu \tag{3.10}$$

Now consider,

$$\begin{aligned}
d(TSu, Tu) &\leq d(TSu, Tx_m) + d(Tx_m, Tu)\\
d(TSu, Tu) &\leq \alpha\Big[d(Tx_{m-1}, TSu) + d(Tu, Tx_m)\Big] + \beta d(Tu, Tx_{m-1})\\
&\quad + d(Tx_m, Tu)\\
d(TSu, Tu) &\leq \alpha\Big[d(Tx_{m-1}, Tu) + d(Tu, Tx_m) + d(Tu, Tx_m)\Big]\\
&\quad + \beta d(Tu, Tx_{m-1}) + d(Tx_m, Tu)\\
d(TSu, Tu) &\leq \frac{\alpha+\beta}{1-\alpha}\big\{d(Tx_{m-1}, Tu) + d(Tu, Tx_m)\big\} + \frac{\alpha+1}{1-\alpha}d(Tx_m, Tu)\\
d(TSu, Tu) &\leq \frac{\alpha+\beta}{1-\alpha}\big\{d(Tx_{m-1}, Tu)\big\} + \frac{2\alpha+\beta+1}{1-\alpha}d(Tx_m, Tu) \qquad (3.11)
\end{aligned}$$

Let $0 \ll c$ be arbitrary, By (3.9), we have

$$d(Tu, Tx_m) \ll \frac{c(1-\alpha)}{2(2\alpha+\beta+1)}$$

And by (3.10) we have

$$d(Tx_{m-1}, Tx_m) \ll \frac{c(1-\alpha)}{2(\alpha+\beta)}$$

Then (3.11) becomes,

$$d(TSu, Tu) \ll c \text{ for each } c \in \operatorname{int} P$$

Now, Using Corollary (2.10-iii), it follows that $d(TSu, Tu) = 0$ which implies that $Tu = TSu$

Since T is one-to-one, Thus u is the fixed point of S.

We claim that, u is the fixed point of.

If w is another fixed point of S, then $w = Sw$

$$\begin{aligned}
d(Tu, Tw) &= d(TSu, TSw)\\
&\leq \alpha\Big(d(Tw, TSu) + d(Tu, TSw)\Big) + \beta d(Tu, Tw)\\
&\leq (2\alpha+\beta)d(Tu, Tw)
\end{aligned}$$

This is a contradiction. Hence $d(Tu, Tw) = 0 \Rightarrow Tu = Tw$. As T is injective, $u = w$. Therefore the fixed point of S is unique.

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