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A FIXED POINT THEOREM FOR (F,Φ)-WEAK CONTRACTION ON COMPLETE METRIC SPACE

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Abstract. By introducing the notion of (F,ϕ) - weak contraction, we establish a fixed point result using this (F,ϕ)-weak contraction. Our result generalize and extend some well known results in the literature.

Keywords: metric space; fixed point; F-contraction.

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1. Introduction

Throughout this article, we denote by (X,d) a metric space (MS) with metric d, by $\mathbb{N}$ the set of all natural numbers, by $\mathbb{R}$ the set of all real numbers and by $\mathbb{R}_+$ the set of all positive real numbers.

2. Preliminaries

In 1922, a famous result called Banach Contraction Principle (BCP) was proved by S. Banach [1] and can be stated as follows.

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Theorem 2.1. [1] *Let (X,d) be a complete MS and $T : X \to X$ be a mapping satisfying*

$$d(Tx,Ty) \leq kd(x,y) \tag{2.1}$$

$\forall x,y \in X$ and $k \in (0,1)$. Then T has a unique fixed point (FP) in X.

Since then many generalizations were developed with modifications of the right of inequality (2.1) (see [2], [4], [6],[7]).

Replacing the constant k in (2.1) by a function, Boyd and Wong [2] established the following result.

Theorem 2.2. [2]. *Let (X,d) be a complete MS and $T : X \to X$ be a mapping. If there exists an upper semicontinuous from the right function $\phi : [0,\infty) \to [0,\infty)$ s.t. $\phi(t) \leq t$ for $t \in (0,\infty)$ and $\forall x,y \in X$*

$$d(Tx,Ty) \leq \phi\ d(x,y) \tag{2.2}$$

then the mapping T has a unique FP x^* and the iterative sequence $\{T^n x\}$ converges to x^*, $\forall\ x \in X$.

Conditions on the function ϕ were modified by many authors (see[5], [6], [7][8]).

Another approach of modifying right of (2.1) is due to Ciric[4].

Theorem 2.3. [4]. *Let (X,d) be a complete MS. Let $T : X \to X$ be a mapping s.t. for some constant $\alpha \in (0,1)$ and $\forall\ x,y \in X$,*

$$d(Tx,Ty) \leq \alpha \max\{d(x,y), d(x,Tx), d(y,Ty), d(x,Ty), d(y,Tx)\} \tag{2.3}$$

Then T has a unique FP.

A generalization similar to the combination of forms (2.2) and (2.3) was used by Pant [7].

Theorem 2.4. [7]. *Let T be a self-mapping of a complete MS (X,d) s.t $\forall\ x,y \in X$,*

$$d(Tx,Ty) \leq \phi\ (M(x,y)) \tag{2.4}$$

where $M(x,y) = max\left\{d(x,Tx), d(y,Ty), \frac{d(x,Ty)+d(y,Tx)}{2}\right\}$, $\phi : \mathbb{R}_+ \to \mathbb{R}_+$ denotes a function s.t. ϕ(t)$< t$ for each $t > 0$ and $\lim_{n\to\infty} \phi^n(t) = 0$. Then T has a unique FP say z. Moreover, T is continuous at z iff $\lim_{x_n\to z} M(x_n, z) = 0$.

Besides these, Wardowski [11] introduced a new notion called F- contraction and gave examples showing that his new notion is a generalization of Banach contraction.

Definition 2.5. [11] *Let $F : \mathbb{R}_+ \to \mathbb{R}$ be a mapping such that*

(F1) F is strictly increasing i.e $\forall\ \alpha, \beta \in \mathbb{R}_+$ s.t. $\alpha < \beta$, then $F(\alpha) < F(\beta)$

(F2) for each sequence $\{\alpha_n\}$ of positive numbers, $\lim_{n\to\infty} \alpha_n = 0$ iff $\lim_{n\to\infty} F(\alpha_n) = -\infty$

(F3) there exists $k \in (0,1)$ s.t. $\lim_{\alpha\to 0^+} \alpha^k F(\alpha) = 0$.

A mapping $T : X \to X$ is called F-contraction if $\exists\ \tau > 0$ such that

$$\forall\, x,y \in X,\ d(Tx,Ty) > 0 \implies \tau + F(d(Tx,Ty)) \leq F(d(x,y)) \tag{2.5}$$

Examples of F- contraction are given in [11].

Using F-contraction, Wardowski [11] proved the following theorem generalizing BCP.

Theorem 2.6. [11] *Let (X,d) be a complete MS and let $T : X \to X$ be an F- contraction. Then T has a unique FP $x^* \in X$ and for every $x_0 \in X$ a sequence $\{T^n x_0\}_{n\in\mathbb{N}}$ is convergent to x^*.*

In 2014, Wardowski and Dung[12] generalized F- contraction into F-weak contraction as follows.

Definition 2.7. [12] *.Let (X,d) be a MS. $T : X \to X$ is called F-weak contraction on (X,d) if $\exists\ \tau > 0$ s.t. $\forall\, x,y \in X$ with $d(Tx,Ty) > 0$, implies that*

$$\tau + F(d(Tx,Ty)) \leq F\left(\max\left\{d(x,y), d(x,Tx), d(y,Ty), \frac{d(x,Ty)+d(y,Tx)}{2}\right\}\right) \tag{2.6}$$

Remark 2.8. [12]

Every F-contraction is an F-weak contraction but the converse is not necessarily true (see example [12]*).*

Using this notion of F- weak contraction, the authors proved the following theorem extending Wardowski [11] theorem (2.1)

Theorem 2.9. [12] *Let (X,d) be a complete MS and $T : X \to X$ be a F - weak contraction. If $TorF$ is continuous, then*

(1) T has a unique FP $x^* \in X$.

(2) $\forall\, x \in X$, $\{T^n x\}$ is convergent to x^*.

Recently, Lukacs and Kajanto[5], proved the following Lemma.

Lemma 2.10. [5] *If $F : (0,\infty) \to \mathbb{R}$ is an increasing function and $\{\alpha_n\}_{n\in\mathbb{N}} \subset (0,+\infty)$ is a decreasing sequence s.t.*

$\lim_{n\to\infty} F(\alpha_n) = -\infty$ *then* $\lim_{n\to\infty} \alpha_n = 0.$

Also in [8], Peri and Kumam used new condition $(F3')$ instead of $(F3)$ of Wardowski [11] which is stated as

$(F3')$ F is continuous on $(0,\infty)$.

Now, we denote by $\Im$ the family of all functions satisfying $(F1)$ and $(F3')$.

Example 2.11. *Let $F_1(x) = 2x, F_2(x) = x^n + x, n > 0$.Then $F_1, F_2, F_3 \in \Im$.*

It is noted that condition $(F3)$ and $(F3')$ are independent ([8],Remark 1.1).

Let $M(x,y) = \max\left\{d(x,y), d(x,Tx), d(y,Ty), \frac{d(x,Ty)+d(y,Tx)}{2}\right\}$.

Clearly, $\max\left\{a,b,c,\frac{e+f}{2}\right\} \leq \max\{a,b,c,e,f\}\ \forall\, a,b,c,e,f \in \mathbb{R}$.

In this paper, by considering $M(x,y) = \max\{d(x,y), d(x,Tx), d(y,Ty), d(x,Ty), d(y,Tx)\}$, we define (F,ϕ) - weak contraction and prove a FP theorem for (F,ϕ) - weak contraction which generalised some well known result in the literature.

3. Main Results

In the following we use the definition

Definition 3.1. *Let Φ be a family of functions $\phi : \mathbb{R}_+ \to \mathbb{R}_+$ satisfying:*

$(\phi 1)$ *ϕ is non decreasing and continuous,*

$(\phi 2)$ $\phi(2t) < t$ *for* $t \in \mathbb{R}_+$.

Remark 3.2. *For $t \in (0,\infty)$,we consider that $\phi(2t) < t$ implies that $\phi(t) < t$ but not conversely.*

Example 3.3. *Let $\phi : \mathbb{R}_+ \to \mathbb{R}_+$ be defined by $\phi(t)= \frac{2}{3}t$.Then ϕ is non-decreasing, continuous and $\phi(t) < t \; \forall \; t \in \mathbb{R}_+$. But $\phi(2t)=\frac{2}{3}(2t) = \frac{4}{3}t > t$, so that $\phi(t) < t$ does not imply $\phi(2t) < t$. Now, we define(F,ϕ)-we contraction as follows.*

Definition 3.4. *Let (X,d) be a MS. A mapping $T : X \to X$ is called (F,ϕ) -weak contraction on (X,d) if $\exists \; \tau > 0$ with $F \in \Im$ and $\phi \in \Phi$ s.t $\forall \; x,y \in X$,*

$$d(Tx,Ty) > 0 \implies \tau + F(d(Tx,Ty)) \leq F(M(x,y)) \tag{3.1}$$

where

$$M(x,y) = \phi\left(\max\{d(x,y),d(x,Tx),d(y,Ty),d(x,Ty),d(y,Tx)\}\right) \tag{3.2}$$

Remark 3.5. *Let T be (F,ϕ)- weak contraction. Then from (3.1), $\forall \; x,y \in X, \; Tx \neq Ty$*

$$F(d(Tx,Ty)) < \tau + F(d(Tx,Ty)) \leq F(\phi(\max\{(x,y),d(x,Tx),d(y,Ty),d(x,Ty),d(y,Tx)\}))$$

Since $\phi(2t) < t \implies \phi(t) < t$, for $t > 0$, therefore $\forall \; x,y \in X, \; Tx \neq Ty$

$$F(d(Tx,Ty)) < \tau + F(d(Tx,Ty)) \leq F(\max\{d(x,y),d(x,Tx),d(y,Ty),d(x,Ty),d(y,Tx)\})$$

Then by $(F1)$, we have

$$d(Tx,Ty) < \max\{d(x,y),d(x,Tx),d(y,Ty),d(x,Ty),d(y,Tx)\} \; \forall \; x,y \in X, Tx \neq Ty$$

Example 3.6. *Let $X = [0,1]$ and d be the usual metric on X i.e*
$d(x,y) = \mid x-y \mid, \forall \; x,y \in X$

Define $T : X \to X$ as

$$Tx = \begin{cases} \frac{x}{3}, \; x \in [0,1) \\ \frac{1}{3}, \; x = 1 \end{cases}$$

$\forall \; x,y \in [0,1], x \neq y$,

$$d(Tx,Ty) = \mid \frac{x}{3} - \frac{y}{3} \mid = \frac{1}{3} \mid x-y \mid = \frac{1}{3} d(x,y)$$

and

$$d(x,y) \leq \max\{d(x,y),d(x,Tx),d(y,Ty),d(x,Ty),d(y,Tx)\}$$

Therefore , taking $F(x) = 2x$ and $\phi(x) = \frac{4x}{9}$, we can find a real no. $\tau > 0$ (say $\tau = \frac{1}{10}$) s.t. (3.1) holds. Hence T is (F,ϕ) - weak contraction. Now we state our main result.

Theorem 3.7. *Let (X,d) be a complete MS and let $T : X \to X$ be a (F,ϕ) - weak contraction. Then, T has a unique FP $x^* \in X$.*

Proof: Let $x_0 \in X$ be a arbitrary and fixed. Define $\{x_n\}_{n\in\mathbb{N}} \subset X$ s.t. $x_{n+1} = Tx_n, n = 0,1,2,....$
If $\exists\ n_0 \in \mathbb{N}$ s.t. $x_{n_0+1} = x_{n_0}$, then $Tx_{n_0} = x_{n_0}$ and the proof is completed.
Suppose $x_{n+1} \neq x_n\ \forall\ n \in \mathbb{N}$. Then by (7), $\forall\ n \in \mathbb{N}$,

$$F(d(x_{n+1},x_n)) = F(d(Tx_n,Tx_{n-1})) \leq F(M(x_n,x_{n-1})) - \tau \tag{3.3}$$

where

$$M(x_n,x_{n-1}) = \phi(\max\{d(x_n,x_{n-1}),d(x_n,Tx_n),d(x_{n-1},Tx_{n-1}),d(x_n,Tx_{n-1}),d(x_{n-1},Tx_n)\})$$

$$= \phi(\max\{d(x_n,x_{n-1}),d(x_n,x_{n+1}),d(x_{n-1},x_n),d(x_n,x_n),d(x_{n-1},x_{n+1})\})$$

$$= \phi(\max\{d(x_n,x_{n-1}),d(x_{n+1},x_n),d(x_n,x_{n-1}),d(x_n,x_n),d(x_n,x_{n-1})+d(x_{n+1},x_n)\})$$

$$= \phi\,(d(x_n,x_{n-1})+d(x_{n+1},x_n))$$

If $d(x_{n+1},x_n) > d(x_n,x_{n-1})$, then from (3.3), using $(\phi 2)$

$$F(d(x_{n+1},x_n)) \leq F(\phi(2d(x_{n+1},x_n))) - \tau \leq F(d(x_{n+1},x_n)) - \tau < F(d(x_{n+1},x_n))$$

which is a contradiction. Hence, $d(x_{n+1},x_n) < d(x_n,x_{n-1})\ \forall\ n \in \mathbb{N}$.
Thus, from (3.3), $F(d(x_{n+1},x_n)) \leq F(d(x_n,x_{n-1})) - \tau\ \forall\ n \in \mathbb{N}$.
It follows that

$$F(d(x_{n+1},x_n)) \leq F(d(x_1,x_0)) - n\tau \tag{3.4}$$

$\forall\ n \in \mathbb{N}$.

Letting $n \to \infty$ in (3.4), we have $\lim_{n\to\infty} F(d(x_{n+1},x_n)) = -\infty$.

Since $\{d(x_{n+1},x_n)\}_{n\in\mathbb{N}}$ is a decreasing sequence of positive real numbers s.t. $\lim_{n\to\infty} F(d(x_{n+1},x_n)) = -\infty$. Then by Lemma 2.10,

$$\lim_{n\to\infty} d(x_{n+1},x_n) = 0$$

$$i.e \lim_{n\to\infty} d(Tx_n, x_n) = 0 \tag{3.5}$$

Suppose that $\{x_n\}_{n\in\mathbb{N}}$ is not a Cauchy sequence. Then $\forall\ \varepsilon > 0\ \exists\ \{p(n)\}_{n\in\mathbb{N}}$ and $\{q(n)\}_{n\in\mathbb{N}}$ with $p(n) > q(n) > n$ s.t.

$$d(x_{p(n)}, x_{q(n)}) \geq \varepsilon \tag{3.6}$$

Suppose $p(n)$ is the smallest integer greater than $q(n)$ which satisfy (3.6) i.e. $d(x_{p(n)-1}, x_{q(n)}) < \varepsilon\ \forall\ n \in \mathbb{N}$.

Then , $\forall\ n \in \mathbb{N}$

$$\begin{aligned}
\varepsilon \leq d(x_{p(n)}, x_{q(n)}) &\leq d(x_{p(n)}, x_{p(n)-1}) + d(x_{p(n)-1}, x_{q(n)}) \\
&\leq d(x_{p(n)}, x_{p(n)-1}) + \varepsilon \\
&= d(Tx_{p(n)-1}, x_{p(n)-1}) + \varepsilon.
\end{aligned}$$

Letting $n \to \infty$ and using (3.5).

$$\varepsilon \leq \lim_{n\to\infty} d(x_{p(n)}, x_{q(n)}) < \varepsilon\ i.e. \lim_{n\to\infty} d(x_{p(n)}, x_{q(n)}) = \varepsilon \tag{3.7}$$

Since $\lim_{n\to\infty} d(Tx_n, x_n) = 0\ \exists\ k \in \mathbb{N}$ s.t.

$$d(x_{p(n)}, Tx_{p(n)}) \leq \frac{\varepsilon}{4} \tag{3.8}$$

and

$$d(x_{q(n)}, Tx_{q(n)}) \leq \frac{\varepsilon}{4} \tag{3.9}$$

$\forall\ n \geq k$. For this k, we claim that

$$d(Tx_{p(n)}, Tx_{q(n)}) = \varepsilon > 0$$

$\forall\ n \geq k$. Assume that $\exists\ m \geq k$ s.t. $d(Tx_{p(m)}, Tx_{q(m)}) = 0$, i.e

$$d(x_{p(m)+1}, x_{q(m)+1}) = 0 \tag{3.10}$$

From (3.6) using (3.8), (3.9) and (3.10), we have

$$\varepsilon \leq d(x_{p(m)}, x_{q(m)}) \leq d(x_{p(m)}, x_{p(m)+1}) + d(x_{p(m)+1}, x_{q(m+1)}) + d(x_{q(m)+1}, x_{q(m)})$$

$$\begin{aligned} &= d(x_{p(m)},Tx_{p(m)})+d(x_{p(m)+1},x_{q(m)+1})+d(x_{q(m)},Tx_{q(m)}) \\ &< \frac{\varepsilon}{4}+0+\frac{\varepsilon}{4} \\ &= \frac{\varepsilon}{2} \end{aligned}$$

a contradiction. Therefore

$$d(Tx_{p(n)},Tx_{q(n)})=\varepsilon>0$$

$\forall\, n\geq k$. Then by (3.1), $\forall\, n\geq k$

$$F(d(Tx_{p(n)},Tx_{q(n)}))\leq F(M(x_{p(n)},x_{q(n)}))-\tau \tag{3.11}$$

where

$$\begin{aligned} M(x_{p(n)},x_{q(n)}) &= \phi\left(\max\left\{d(x_{p(n)},x_{q(n)}),d(x_{p(n)},Tx_{p(n)}),d(x_{q(n)},Tx_{q(n)}),\right.\right. \\ &\qquad \left.\left. d(x_{p(n)},Tx_{q(n)}),d(x_{q(n)},Tx_{p(n)})\right\}\right) \\ &\leq \phi\left(\max\left\{d(x_{p(n)},x_{q(n)}),d(x_{p(n)},Tx_{p(n)}),d(x_{q(n)},Tx_{q(n)}),\right.\right. \\ &\qquad \left.\left. d(x_{p(n)},x_{q(n)})+d(x_{q(n)},Tx_{q_(n)}),d(x_{p(n)},x_{q(n)})+d(x_{p(n)},Tx_{p(n)})\right\}\right) \\ &= \phi(d(x_{p(n)},x_{q(n)})+\frac{\varepsilon}{4}) \end{aligned}$$

Letting $n\to\infty$ in (3.11) and using $(F1)$,$(F3')$,$(\phi 1)$ and $(\phi 2)$,

$$\begin{aligned} F(\varepsilon)\leq F(\phi(\varepsilon+\frac{\varepsilon}{4}))-\tau & \\ &\leq F(\phi(2\varepsilon))-\tau \\ &\leq F(\varepsilon)-\tau \\ &< F(\varepsilon) \end{aligned}$$

a contradiction. Thus $\{x_n\}_{n\in\mathbb{N}}$ is a Cauchy.

Since (X,d) is complete, then $\exists\, x^*\in X$ s.t. $\lim_{n\to\infty} x_n=x^*$.

Now we shall prove that x^* is a FP of$T$.

By $(F3')$, we will consider two cases.

Case I: If there exists subsequence $\{x_{n_i}\}_{i\in\mathbb{N}}$ of $\{x_n\}_{n\in\mathbb{N}}$ s.t. $x_{n_i}=Tx^*\ \forall\ i\in\mathbb{N}$, then $x^*=\lim_{i\to\infty} x_{n_i}=\lim_{i\to\infty} Tx^*=Tx^*$

Case II : If $\exists$ no such subsequence of $\{x_n\}_{n\in\mathbb{N}}$, then $\exists\ n_0 \in \mathbb{N}$ s.t. $x_{n+1} \neq Tx^* \ \forall\ n \geq n_0$ i.e $d(Tx_n, Tx^*) > 0 \ \forall\ n \geq n_0$. Then, by (3.1)

$$\tau + F(d(x_{n+1}, Tx^*)) = \tau + F(d(Tx_n, Tx^*)) \leq F(M(x_n, x^*)) \tag{3.12}$$

where

$$\begin{aligned} M(x_n, x^*) &= \phi(\max\{d(x_n, x^*), d(x_n, Tx_n), d(x^*, Tx^*), d(x_n, Tx^*), d(x^*, Tx_n)\} \\ &\leq \phi(\max\{d(x_n, x^*), d(x_n, x_{n+1}), d(x^*, Tx^*), \\ &\qquad d(x_n, x^*) + d(x^*, Tx^*), d(x^*, x_{n+1})\} \end{aligned} \tag{3.13}$$

We know that $\lim\limits_{n\to\infty} d(x_n, x^*) = \lim\limits_{n\to\infty} d(x_{n+1}, x^*) = 0$, then letting $n \to \infty$ in (3.13) and using $(\phi 1)$ and$(\phi 2)$, we have

$$\begin{aligned} \lim_{n\to\infty} Mx_n, x^*) &= \phi(d(x^*, Tx^*)) \\ &\leq \phi(2d(x^*, Tx^*)) < d(x^*, Tx^*) \end{aligned} \tag{3.14}$$

Letting $n \to \infty$ in (3.12) and using $(F1)$,$(F3')$ and (3.14) we have

$$\tau + F(d(x^*, Tx^*)) \leq F(d(x^*, Tx^*))$$

a contradiction as $\tau > 0$. Hence

$$d(x^*, Tx^*) = 0$$

that is x^* is a FP of T.

Now we prove that the FP is unique.

Let x_1^*, x_2^* be two FP of T. Suppose, if possible, that $x*_1 \neq x_2^*$. Then $Tx_1^* \neq Tx_2^*$. Then from (3.1)

$$\begin{aligned} \tau + F(d(x_1^*, x_2^*)) &= \tau + F(d(Tx_1^*, Tx_2^*)) \\ &\leq F(M(x_1^*, x_2^*)) \end{aligned} \tag{3.15}$$

where

$$\begin{aligned} M(x_1^*, x_2^*) &= \phi\left(\max\{d(x_1^*, x_2^*), d(x_1^*, Tx_1^*), d(x_2^*, Tx_2^*), d(x_1^*, Tx_2^*), d(x_2^*, Tx_1^*)\}\}\right) \\ &\leq \phi \max\{d(x_1^*, x_2^*), d(x_1^*, Tx_1^*), d(x_2^*, Tx_2^*), d(x_1^*, x_2^*) + d(x_2^*, Tx_2^*), d(x_1^*, x_2^*) + d(x_1^*, Tx_1^*)\}) \end{aligned}$$

$$\begin{aligned} &= \phi(d(x_1^*, x_2^*)) \\ &\leq \phi(2d(x_1^*, x_2^*)) \\ &< d(x_1^*, x_2^*) \end{aligned}$$

Therefore, from (3.15), we have

$$\tau + F(d(x_1^*, x_2^*)) \leq F(d(x_1^*, x_2^*))$$

which implies that $\tau \leq 0$, a contradiction. Hence $x_1^* = x_2^*$.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests.

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