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Fixed Point Theorems in Fuzzy Metric Spaces for Occasionally Weakly Compatible Mappings

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Abstract—*In this paper we tried to prove fixed point theorem using concept of occasionally weakly compatible mapping. occasionally weakly compatible mapping is more particular form of compatible mapping in this type mappings coincidence point are less compared to compatible mappings.*

Keywords***: C****ompatible mappings, Cauchy sequence, Fuzzy metric space, Point of coincidence, Reciprocal continuous mappings, t-norm, Weakly compatible mappings.*

1. INTRODUCTION AND PRELIMINARY CONCEPTS :

In 1986, Jungck [12] introduced the notion of compatible mappings for a pair of self mappings, Jungck and Rhoades [13] introduced the notion of weak compatible mapping by weakening the concept of compatibility. The concept of weakly compatible mappings is more general as each pair of compatible mappings is weakly compatible but the reverse is not true. More recently, Al-Thagafi and N. Shahzad [8] weakened the concept of compatibility by giving a new notion of occasionally weakly compatible mappings which is more general among all the commutative concepts. No wonder that the notion of occasionally weakly compatible mappings has become an area of interest for specialists in fixed point theory, see [1], [2], [3], [4], [5], [6] and [7]. In recent years several fixed point theorems for single and set valued mappings are proved which have numerous applications and by now, there exists a considerable and rich literature in this domain. Various authors have discussed and studied extensively various results on coincidence, existence and uniqueness of fixed point and common fixed points by using the concept of weak commutativity, compatibility, non-compatibility and weak compatibility for single and set valued mappings satisfying certain contractive conditions in different spaces and they have been applied to diverse problems. Note that common fixed point theorems for single and set valued mappings are interesting and play a major role in many areas.

Definition 1.1.1 [18] : A binary operation*: $[0,1] \times [0,1] \rightarrow [0,1]$ is continuous t-norm if it satisfies the following conditions:

(1.1.1) * is commutative and associative;

(1.1.2) * is continuous;

(1.1.3) a *1 = a, for all $a \in [0,1]$;

(1.1.4) $a * b \leq c * d$, whenever $a \leq c$ and $b \leq d$ for all $a, b, c, d \in [0,1]$;

Examples of t-norm are $a * b = \min\{a, b\}$ and $a * b = ab$.

Definition 1.2 [19] : A 3-tuple $(X, M,*)$ is said to be a fuzzy metric space if X is an arbitrary set, $*$ is a continuous t-norm and M is a fuzzy set on $X^2 \times [0, \infty)$ satisfying the following conditions;

(1.2.1) $M(x, y, 0) = 0$, for all $x, y \in X$;

(1.2.2) $M(x, y, t) = 1$, for all $x, y \in X$ and $t > 0$ if and only if $x = y$;

(1.2.3) $M(x, y, t) = M(y, x, t)$ for all $x, y \in X$ and $t > 0$;

(1.2.4) $M(x, y, t) * M(y, z, s) \leq M(x, z, t + s)$, for all $x, y, z \in X$;

and $s, t > 0$, the function $M(x, y, t)$ denote the degree of nearness between x and y with respect to t.

Remark 1.1 [11] : In a fuzzy metric space $(X, M,*), M(x, y, .)$ is non-decreasing for all $x, y \in X$.

Definition 1.3 [11] : Let $(X, M,*)$, be a fuzzy metric space. Then

(1.3.1) A sequence $\{x_n\}$ in X is said to be Cauchy sequence if for all $t > 0$ and $p > 0$,

$$\lim_{n\to\infty} M(x_{n+p}, x_n, t) = 1$$

(1.3.2) A sequence $\{x_n\}$ in X is said to be convergent to a point $x \in X$ if for all $t > 0$

$$\lim_{n\to\infty} M(x_n, x, t) = 1$$

Definition 1.4 [11] : A pair (A, B) of self mappings of a fuzzy metric space $(X, M,*)$ is said to be reciprocal continuous if

$\lim_{n\to\infty} ABx_n = Ax$ and $\lim_{n\to\infty} BAx_n = Bx$

whenever there exists a sequence $\{x_n\} \in X$ such that

$\lim_{n\to\infty} Ax_n = \lim_{n\to\infty} Bx_n = x$ for some $x \in X$.

Definition 1.5 [13] : A fuzzy metric space $(X, M,*)$ is said to be complete if and only if every Cauchy sequence in X is convergent.

Definition 1.6 [23] : Let A and S be mappings from a fuzzy metric $(X, M,*)$ into itself, then mappings A and S are said to be weakly compatible if

$M(ASz, SAz, t) \geq M(Az, Sz, t)$, for all $z \in X$ and $t > 0$.

Definition 1.7 [9] : Let A and S be mappings from a fuzzy metric space $(X, M,*)$ into itself. Then mappings A and S are said to be compatible if for all $t > 0$

$$\lim_{n\to\infty} M(ASx_n, SAx_n, t) = 1$$

whenever $\{x_n\}$ is a sequence in X such that

$\lim_{n\to\infty} Ax_n = \lim_{n\to\infty} Sx_n = z$ for some $z \in X$.

Definition 1.8 [24] : Let A and S be self mappings on X. A point x in X is called a coincidence point of A and S if and only if

$$Ax = Sx$$

in this case

$$w = Ax = S\,x$$

is called a point of coincidence of A and S.

Definition 1.9 [20] : A pair of mappings (A, S) of a fuzzy metric space $(X, M,*)$ is said to be weakly compatible if they commute at their coincident points i.e., if

$$Au = Su$$

for some u in X then

$ASu = SAu.$

Definition 1.10 [14] : Two self mappings A and S of a fuzzy metric space $(X, M,*)$ are said to be occasionally weakly compatible if and only if there is a point x in X which is coincidence point of A and S at which A and S commute.

Example 1.1 [22] : Let $X = [1, \infty)$ with metric d. We define

$$M(x, y, t) = \frac{t}{t + d(x, y)}$$

for all x, y in $X, t > 0$. Let $*$ be any continuous t-norm. Then $(X, M,*)$ is a fuzzy metric space.

Let A and B be self mappings on X defined by,

$Ax = 5x - 4, x \in X$ and $Bx = x^2, x \in X$

then 1 and 4 are the only points of coincidence of A and B.

Also

$AB(1) = BA(1)$ but $AB(4) = 76 \neq BA(4) = 256.$

Clearly A and B are occasionally weakly compatible but not weakly compatible.

Example 1.2 [10] : Let $X = [0, 10]$ with metric d defined by

$$d(x, y) = |x - y|$$

and for each $t \in [0, 1]$ define

$$M(x, y, t) = \begin{cases} \dfrac{t}{t + d(x, y)} & if\ t > 0 \\ 0 & if\ t = 0 \end{cases}$$

for all $x, y \in X$. Clearly $(X, M,*)$ is a fuzzy metric space, where $a * b = \min\{a, b\}$ for all $a, b \in [0, 1]$. Define the self mappings A, B, S and T such that

$$Ax = \begin{cases} x & if\ 0 \leq x \leq 5 \\ 10 & if\ 5 < x \leq 10 \end{cases}$$

$$Bx = \begin{cases} 5 & if\ 0 \leq x \leq 5 \\ 10 & if\ 5 < x \leq 10 \end{cases}$$

$$Sx = \begin{cases} 5 & if\ 0 \leq x \leq 5 \\ 0 & if\ 5 < x \leq 10 \end{cases}$$

$$Tx = \begin{cases} 5 & if\ 0 \leq x \leq 5 \\ \frac{x}{10} & if\ 5 < x \leq 10 \end{cases}$$

first we have

$A(5) = 5 = S(5), AS(5) = SA(5) = 5$ and $T(5) = 5 = B(5), BT(5) = 5 = TB(5)$,

that is A and S as well B and T are occasionally weakly compatible mappings and have a unique common fixed point 5. Also all the mappings are discontinuous at 5.

Definition 1.11 [21] : Let Φ_4 be the set of all real and continuous functions, $\emptyset \in \Phi_4$ and $\emptyset : (R^+)^4 \to R$ such that,

(1.11.1) $\emptyset$ is non-increasing in $2^{nd}, 3^{rd}$ and 4^{th} argument and,

(1.11.2) for $u, v \geq 0$ $\emptyset(u, v, v, v) \geq 0 \Rightarrow u \geq v$.

Example 1.3 $\emptyset(t_1, t_2, t_3, t_4) = t_1 - max\{t_2, t_3, t_4\}$

Lemma 1.1 [17] : Let $(X, M,*)$ be a fuzzy metric space and for all

$x, y \in X, t > 0$ and if for a number $k \in (0,1)$

$$M(x, y, kt) \geq M(x, y, t)$$

then $x = y$.

Lemma 1.2 [17] : Let $\{u_n\}$ be a sequence in a fuzzy metric space $(X, M,*)$. If there exists a constant $k \in (0,1)$ such that

$$M(u_n, u_{n+1}, kt) \geq M(u_{n-1}, u_n, t)$$

for all $t > 0$ and $n = 1,2,3 \ldots$ then $\{u_n\}$ is a Cauchy sequence in X.

Lemma 1.3 [12]: Let X be a non empty set, f and g be occasionally weakly compatible self mappings of X. If f and g have a unique point of coincidence i.e.

$$w = fx = gx,$$

then w is the unique common fixed point of f and g.

1.2 Occasionally weakly compatible mapping for fuzzy metric spaces

Mishra and Chaudhary [16] proved the following theorem with four mappings -

Theorem 1.2.1 [15] : Let $(X, M,*)$ be a complete fuzzy metric space and let A, B, S and T be self mappings of X. Let the pairs $\{A, S\}$ and $\{B, T\}$ be occasionally weakly compatible. If there exists $q \in (0,1)$ and

$$(1.2.1)\ M(Ax, By, qt) \geq min \left\{ \begin{matrix} M(Sx, Ty, t), M(Sx, Ax, t), M(By, Ty, t), \\ \left[\dfrac{M(Ax, Ty, t) + M(By, Sx, t)}{2}\right] \end{matrix} \right\}$$

for all $x, y \in X$ and for all $t > 0$, then there exist a unique point $w \in X$ such that $Aw = Sw = w$ and a unique point $z \in X$ such that $Bz = Tz = z$. Moreover $z = w$, so that there is a unique common fixed point of A, B, S and T.

We prove the following common fixed point theorem using occasionally weakly compatible mappings -

Theorem 1.2.2 : Let $(X, M,*)$ be a complete fuzzy metric space and let A, B, S and T be self mappings of X. Let the pairs $\{A, S\}$ and $\{B, T\}$ be occasionally weakly compatible. If for $\emptyset \in \Phi_4$ satisfying (1.11.1), (1.11.2), and;

$$(1.2.1)\ A(X) \subseteq T(X), B(X) \subseteq S(X),$$

(1.2.2) the pairs (A, S) and (B, T) are occasionally weakly compatible,

(1.2.3) there exists $k \in (0,1)$ such that for all $x, y \in X$ and $t > 0$,

$$\emptyset \left(\begin{matrix} M(Ax, By, kt), M(Sx, Ty, t), M(Sx, Ax, t), \\ \dfrac{M(Sx, Ax, t) + M(Sx, Ty, t)}{2} \end{matrix} \right) \geq 0$$

then A, B, S and T have a common fixed point in X.

Proof: Let $x_0 \in X$ be an arbitrary point. As $A(X) \subseteq T(X)$ and $B(X) \subseteq S(X)$.Then there exists $x_1,\ x_2 \in X$ such that $Ax_0 = Tx_1$ and $Bx_1 = Sx_2$. Inductively, we can construct sequences $\{y_n\}$ and $\{x_n\}$ in X such that

$y_{2n+1} = Ax_{2n} = Tx_{2n+1}, y_{2n+2} = Bx_{2n+1} = Sx_{2n+2,}$ for $n = 0,1,2 \ldots.$

We first show that $\{y_n\}$ is a Cauchy sequence in X. Putting $x = x_{2n}$ and

y = x_{2n+1} in (1.2.3) we have

$$\emptyset \left(\begin{matrix} M(Ax_{2n}, Bx_{2n+1}, kt), M(Sx_{2n}, Tx_{2n+1}, t), M(Sx_{2n}, Ax_{2n}, t), \\ \dfrac{M(Sx_{2n}, Ax_{2n}, t) + M(Sx_{2n}, Tx_{2n+1}, t)}{2} \end{matrix} \right) \geq 0$$

$$\emptyset \left(\begin{matrix} M(y_{2n+1}, y_{2n+2}, kt), M(y_{2n}, y_{2n+1}, t), M(y_{2n}, y_{2n+1}, t), \\ \dfrac{M(y_{2n}, y_{2n+1}, t) + M(y_{2n}, y_{2n+1}, t)}{2} \end{matrix} \right) \geq 0$$

$$\emptyset \left(\begin{matrix} M(y_{2n+1}, y_{2n+2}, kt), M(y_{2n}, y_{2n+1}, t), M(y_{2n}, y_{2n+1}, t), \\ M(y_{2n}, y_{2n+1}, t) \end{matrix} \right) \geq 0$$

therefore by using (1.11.1) and (1.11.2) we have

$$M(y_{2n+1}, y_{2n+2}, kt) \geq M(y_{2n}, y_{2n+1}, t)$$

similarly, we also have

$M(y_{2n+2}, y_{2n+3}, kt) \geq M(y_{2n+2}, y_{2n+1}, t)$ for all $t > 0$

thus for all n and $t > 0$.

$M(y_n, y_{n+1}, kt) \geq M(y_n, y_{n-1}, t)\ \forall\ t > 0$

therefore

$$M(y_n, y_{n+1}, t) \geq M\left(y_{n-1}, y_n, {}^{t}/_{k}\right) \geq M\left(y_{n-2}, y_{n-1}, {}^{t}/_{k^2}\right) \geq \cdots \geq M\left(y_0, y_1, {}^{t}/_{k^n}\right)$$

hence

$$\lim_{n\to\infty} M(y_n, y_{n+1}, t) = 1\ \forall\ t > 0.$$

Now for any integer $p > 0$ we have

$$M(y_n, y_{n+p}, t) \geq M(y_n, y_{n+1}, {}^{t}/_{p}) * M(y_{n+1}, y_{n+2}, {}^{t}/_{p}) * \ldots * \ldots \ldots * M(y_{n+p-1}, y_{n+p}, {}^{t}/_{p})$$

therefore

$$\lim_{n\to\infty} M(y_n, y_{n+p}, t) = 1 * 1 * 1 * \ldots \ldots . . * 1 = 1.$$

By (1.3) this shows that $\{y_n\}$ is a Cauchy sequence in X which is complete. Therefore $\{y_n\}$ converges to $z \in X$. We have its subsequences $\{Ax_{2n}\}, \{Bx_{2n+1}\}$ $\{Sx_{2n}\}$ and $\{Tx_{2n+1}\}$ converges to z. Since

$A(X) \subseteq T(X)$, there exists $p \in X$ such that

$Tp = z.$

Putting $x = x_{2n}$ and $y = p$ in (1.2.3) we have

$$\emptyset \left(\begin{matrix} M(Ax_{2n}, Bp, kt), M(Sx_{2n}, Tp, t), M(Sx_{2n}, Ax_{2n}, t), \\ \dfrac{M(Sx_{2n}, Ax_{2n}, t) + M(Sx_{2n}, Tp, t)}{2} \end{matrix} \right) \geq 0$$

$$\emptyset\left(M(z,Bp,kt),M(z,z,t),M(z,z,t),\frac{M(z,z,t)+M(z,Tp,t)}{2}\right)$$
$$\geq 0$$

$$\emptyset\left(M(z,Bp,kt),1,1,\frac{1+M(z,z,t)}{2}\right)\geq 0$$

since $\emptyset$ is non-increasing in 4^{th} argument therefore

$$\emptyset(M(z,Bp,kt),1,1,1)\geq 0$$

since $\emptyset$ is non-increasing in 2^{nd}, 3^{rd} and 4^{th} argument therefore

$$\emptyset\big(M(z,Bp,kt),M(z,Bp,t),M(z,Bp,t),M(Bp,z,t)\big)\geq 0$$

by using (1.11.2) we have

$$M(z,Bp,kt)\geq M(z,Bp,t)$$

therefore by using lemma (2.1.1) we have

$$Bp = z$$

i.e. p is coincidence point of B and T. Similarly, since $B(X)\subseteq S(X)$, their exists $q\in X$ such that $Sq = z$. Putting $x = q$ and $y = x_{2n+1}$ in (1.2.3) we have

$$\emptyset\left(\begin{matrix}M(Aq,Bx_{2n+1},kt),M(Sq,Tx_{2n+1},t),M(Sq,Aq,t),\\ \dfrac{M(Sq,Aq,t)+M(Sq,Tx_{2n+1},t)}{2}\end{matrix}\right)\geq 0$$

$$\emptyset\left(M(Aq,z,kt),M(z,z,t),M(z,Aq,t),\frac{M(z,Aq,t)+M(z,z,t)}{2}\right)\geq 0$$

$$\emptyset\left(M(Aq,z,kt),1,M(z,Aq,t),\frac{M(z,Aq,t)+1}{2}\right)\geq 0$$

since $\emptyset$ is non-increasing in 4^{th} argument therefore

$$\emptyset\big(M(Aq,z,kt),1,M(z,Aq,t),M(z,Aq,t),M(z,Aq,t)\big)\geq 0$$

since $\emptyset$ is non-increasing in 2^{nd} argument therefore by using (1.11.1) and

(1.11.2) we have

$$\emptyset\big(M(Aq,z,kt),M(z,Aq,t),M(z,Aq,t),M(z,Aq,t)\big)\geq 0$$

$$M(Aq,z,kt)\geq M(z,Aq,t)$$

therefore by using lemma (1.2) we have

$Aq = z$. Since $Sq = z$, therefore $z = Aq = Sq$ i.e. q is the coincidence point of A and S. Since $\{A,S\}$ is occasionally weakly compatible. Therefore we have

$ASq = SAq$ or $Sz = Az$. Similarly $\{B,T\}$ is occasionally weakly compatible therefore $BTp = TBp$ or $Bz = Tz$. Putting $x = z$ and $y = x_{2n+1}$ in (1.2.3) we have

$$\emptyset\left(\begin{matrix}M(Az,Bx_{2n+1},kt),M(Sz,Tx_{2n+1},t),M(Sz,Az,t),\\ \dfrac{M(Sz,Tx_{2n+1},t)+M(Sz,Az,t)}{2}\end{matrix}\right)\geq 0$$

$$\emptyset\left(\begin{matrix}M(Az,z,kt),M(Az,z,t),M(Az,Az,t),\\ \dfrac{M(Az,z,t)+M(Az,Az,t)}{2}\end{matrix}\right)\geq 0$$

$$\emptyset\left(M(Az,z,kt),M(Az,z,t),1,\frac{M(Az,z,t)+1}{2}\right)\geq 0$$

since $\emptyset$ is non-increasing in 4^{th} argument therefore

$$\emptyset\big(M(Az,z,kt),M(Az,z,t),1,M(Az,z,t)\big)\geq 0$$

since $\emptyset$ is non-increasing in 3^{rd} argument therefore by using (1.11.1) and

(1.11.2) we have

$$\emptyset\big(M(Az,z,kt),M(Az,z,t),M(Az,z,t),M(Az,z,t)\big)\geq 0$$

$$M(Az,z,kt)\geq M(Az,z,t)$$

therefore by using lemma (1.2) we have

$Az = z.$

Since $Az = Sz$, therefore $z = Az = Sz$. Again putting $x = x_{2n}$ and $y = z$ in (2.2.2.3) we have

$$\emptyset\left(\begin{matrix}M(Ax_{2n},Bz,kt),M(Sx_{2n},Tz,t),M(Sx_{2n},Ax_{2n},t),\\ \dfrac{M(Sx_{2n},Ax_{2n},t)+M(Sx_{2n},Tz,t)}{2}\end{matrix}\right)\geq 0$$

$$\emptyset\left(M(z,Bz,kt),M(z,Bz,t),M(z,z,t),\frac{M(z,z,t)+M(z,Bz,t)}{2}\right)\geq 0$$

$$\emptyset\left(M(z,Bz,kt),M(z,Bz,t),1,\frac{1+M(z,Bz,t)}{2}\right)\geq 0$$

since $\emptyset$ is non-increasing in 4^{th} argument therefore

$$\emptyset\big(M(z,Bz,kt),M(z,Bz,t),1,M(z,Bz,t)\big)\geq 0$$

since $\emptyset$ is non-increasing in 3^{rd} argument therefore by using (1.11.1) and

(1.11.2) we have

$$\emptyset\big(M(z,Bz,kt),M(z,Bz,t),M(z,Bz,t),M(z,Bz,t)\big)\geq 0$$

$$M(z,Bz,kt)\geq M(z,Bz,t)$$

therefore by using lemma (2.1.2) we have

$$Bz = z.$$

Since $Bz = Tz$,Therefore $z = Bz = Tz$. Thus we have $z = Az = Sz = Tz$. Hence z is a common fixed point of A,B,S and T.

Uniqueness : Let z_1 and z_2 be two common fixed points mappings $A,B,S,$ and T then $z_1 = Az_1 = Bz_1 = Sz_1 = Tz_1$ and $z_2 = Az_2 = Bz_2 = Sz_2 = Tz_2$.

Putting $x = z_1$ and $y = z_2$ in (1.2.3) we have

$$\emptyset\left(M(Az_1,Bz_2,kt),M(Sz_1,Tz_2,t),M(Sz_1,Az_1,t),\frac{M(Sz_1,Tz_2,t)+M(Sz_1,Az_1,t)}{2}\right)\geq 0$$

$$\emptyset\left(M(z_1,z_2,kt),M(z_1,z_2,t),M(z_1,z_1,t),\frac{M(z_1,z_2,t)+M(z_1,z_1,t)}{2}\right)\geq 0$$

$$\emptyset\left(M(z_1,z_2,kt),M(z_1,z_2,t),1,\frac{M(z_1,z_2,t)+1}{2}\right)\geq 0$$

since $\emptyset$ is non-increasing in 4^{th} argument therefore

$$\emptyset\big(M(z_1,z_2,kt),M(z_1,z_2,t),1,M(z_1,z_2,t)\big)\geq 0$$

since $\emptyset$ is non-increasing in 3rd argument therefore by using (1.11.1) and

(1.11.2) we have

$$\emptyset\big(M(z_1,z_2,kt),M(z_1,z_2,t),M(z_1,z_2,t),M(z_1,z_2,t)\big)\geq 0$$

$$M(z_1,z_2,kt)\geq\ M(z_1,z_2,t)$$

therefore by using lemma (1.1) $z_1 = z_2$. This completes the proof.

Remark 1.2 : Priyanka Nigam and Neeraj Malviya [123] proved similar result in their paper using occasionally weakly compatible mappings, we used implicit relation and occasionally weakly compatible mappings with four arguments which weakened the concept of compatibility.

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