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Fixed Point Theorems Under Strict Contractive Conditions In Fuzzy Metric Spaces

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ABSTRACT: ***In this paper, by using property (E.A.),*** *we prove common fixed point theorems for weakly compatible mappings satisfying strict contractive condition in fuzzy metric spaces.*
Mathematics subject classification*: 54E40, 54E35, 54H25.*
Keywords*: Fuzzy metric space, Compatible mappings, Weakly compatible mappings.*

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I. INTRODUCTION:

In 1986, Jungck [7] introduced the concept of Compatible mapping and proved some common fixed point theorems of compatible mappings in metric space. The notion of fuzzy sets was introduced by Zadeh [17]. Various concepts of fuzzy metric spaces were considered in [8, 9]. Many authors have studied fixed point theory in fuzzy metric spaces. The authors [4, 5, 1 3, 14] have proved fixed point theorems in fuzzy (probabilistic) metric spaces. It is well known that the probabilistic metric space is an important generalization of metric space (sec [14]). Fixed point theory in probabilistic metric spaces can be considered as a part of probabilistic analysis, which is a very dynamic area of mathematical research.

Definition 1.1:
A binary operation $*: [0, 1] \times [0, 1] \to [0, 1]$ is a continuous t-norm if it satisfies the following conditions.
1) $*$ is associative and commutative,
2) $*$ is continuous
3) $a*1=a$ for all $a\in[0,1]$
4) $a*b \le c*d$ whenever $a\le c$ and $b\le d$, for each $a,b,c,d\in[0,1]$.

Two typical examples of continuous t-norm are $a*b = ab$ and $a*b = \min(a, b)$.

Definition 1.2:
A 3-tuple $(X, \mathcal{M}, *)$ is called a fuzzy metric space if X is an arbitrary (non-empty) set, $*$ is a continuous t-norm, and $\mathcal{M}$-is a fuzzy set on $X^2 \times (0, \infty)$, satisfying the following conditions for each $x, y, z\in X$ and $t, s > 0$,
1) $\mathcal{M}(x, y, t) > 0$,
2) $\mathcal{M}(x, y, t) = 1$ if and only if $x= y$,
3) $\mathcal{M}(x, y, t) = \mathcal{M}(p\{x, y\}, t)$ (symmetry) where p is a permutation function,
4) $\mathcal{M}(x, y, t) * \mathcal{M}(y, z, s) \le \mathcal{M}(x, z, t+s)$
5) $\mathcal{M}(x,y,\cdot): (0,\infty) \to[0,1]$ is continuous

Example 1.3:
Let X be a non-empty set and D is the D-metric on X. Denote $a*b = a.b$ for all $a,b\in[0,1]$.
For each $t\in (0, \infty)$, define $\mathcal{M}(x, y, t) = t/ [t + D(x,y)]$ for all $x, y\in X$. It is easy to see that $(X, \mathcal{M},*)$ is a $\mathcal{M}$-fuzzy metric space.

Definition 1.4:
Let A and S be mappings from a fuzzy metric space $(X, \mathcal{M}, *)$ into itself. Then the mappings are said to be weak compatible if they commute at their coincidence point, that is $Ax = Sx$ implies that
$ASx = SAx$.

Definition 1.5:
Let A and B be two self-mappings of a fuzzy metric space $(X, \mathcal{M}, *)$. We say that A and B satisfy the property (E-A), if there exists a sequence $\{x_n\}$ such that $\lim_{n\to\infty} \mathcal{M}(Ax_n, u, t) = \lim_{n\to\infty} \mathcal{M}(Bx_n, u, t) = 1$ for same $u\in X$ and $t>0$.

II. MAIN RESULTS:

Let $\mathcal{F}$ be the set of all fuzzy set on $X^2\times (0, \infty)$ that is $\mathcal{F} = \{f: X^2\times(0, \infty)\to[0,1]\}$.

Definition 2.1:
Let f and $g\in \mathcal{F}$. The algebraic sum $f \oplus g$ of f and g is defined by
$$f(x, y, t) \oplus g(x',y',t) = \sup_{t_1+t_2=t} \min\{f (x, y, t_1) , g(x', y', t_2)\}$$

Throughout this section Φ denotes a family of mappings such that for each $\varphi \in \Phi$, $\varphi:[0,1]^2\to[0,1]$ is continuous and increasing in each co-ordinate variable. Also $\gamma (t) = \varphi (t, t) \geq t$ for every $t\in[0,1]$.

Now, we prove a common fixed point theorem using a property (E-A).

Theorem 2.2:
Let A, B, S and T be mappings from a fuzzy metric space $(X, \mathcal{M}, *)$ into itself satisfying the following conditions. $A(X) \subseteq T(X)$, $B(X) \subseteq S(X)$ $\to$ (2.1).

$$\mathcal{M}(Ax, By, t) \geq \varphi \begin{Bmatrix} \mathcal{M}\left(Sx, Ty, \frac{2t}{k}\right), \mathcal{M}\left(Ax, Sx, \frac{2t}{k}\right) \oplus \mathcal{M}\left(By, Ty, \frac{2t}{k}\right), \\ \mathcal{M}\left(Ax, Ty, \frac{4t}{k}\right) \oplus \mathcal{M}\left(Sx, By, \frac{4t}{k}\right) \end{Bmatrix} \quad \to \ (2.2).$$

for all $x, y\in X$, $t>0$, $\varphi\in\Phi$, and $0 \leq k < 2$. Suppose that one of the pairs (A, S) and(B, T) satisfies the property (E, A). (A, S) and (B,T) are weakly compatible and one of A(X), B(X), S(X) and T(X) is a complete subspace of X. Then A, B, S and T have a unique common fixed point in X.

Proof:
Suppose that the pair (B, T) satisfies the property (E. A) then there exists a sequence $\{x_n\}$ in X such that $\lim_{n\to\infty} \mathcal{M}(Bx_n, z, t) = \lim_{n\to\infty} \mathcal{M}(Tx_n, z, t) = 1$ for some $z\in X$ and all $t>0$. Therefore $\lim_{n\to\infty} \mathcal{M}(Bx_n, Tx_n, t) = 1$ since $B(X) \subseteq S(X)$.
There exists a sequence $\{Y_n\}$ in X such that $Bx_n = SY_n$, hence $\lim_{n\to\infty} \mathcal{M}(Sy_n, z, t) = 1$.
We prove that $\lim_{n\to\infty} \mathcal{M}(Ay_n, z, t) = 1$. Using (2.2) we have

$$\mathcal{M}(Ay_n, Bx_n, t) \geq \varphi \begin{Bmatrix} \mathcal{M}\left(Sy_n, Tx_n, \frac{2t}{k}\right), \mathcal{M}\left(Ay_n, Sy_n, \frac{2t}{k}\right) \oplus \mathcal{M}\left(Bx_n, Tx_n, \frac{2t}{k}\right), \\ \mathcal{M}\left(Ay_n, Tx_n, \frac{4t}{k}\right) \oplus \mathcal{M}\left(Sy_n, Bx_n, \frac{4t}{k}\right)\} \end{Bmatrix}$$
$$= \varphi \begin{pmatrix} \mathcal{M}\left(Bx_n, Tx_n, \frac{2t}{k}\right), \mathcal{M}\left(Ay_n, Bx_n, \frac{2t}{k}\right) \oplus \mathcal{M}\left(Bx_n, Tx_n, \frac{2t}{k}\right), \\ \mathcal{M}\left(Ay_n, Tx_n, \frac{4t}{k}\right) \oplus 1 \end{pmatrix} \to (2.3).$$

Since, $\liminf_{n\to\infty} \mathcal{M}\left(Ay_n, Bx_n, \frac{2t}{k}\right) \oplus \mathcal{M}\left(Bx_n, Tx_n, \frac{2t}{k}\right)$
$$\geq \liminf_{n\to\infty} \min\left\{ \mathcal{M}\left(Ay_n, Bx_n, \frac{2t}{k} - \epsilon\right), \mathcal{M}(Bx_n, Tx_n, \epsilon)\right\}$$
$$= \liminf_{n\to\infty} \mathcal{M}\left\{Ay_n, Bx_n, \frac{2t}{k} - \epsilon\right\}$$
letting $\epsilon\to0$, in the above inequality, we get
$\liminf_{n\to\infty} \mathcal{M}\left\{Ay_n, Bx_n, \frac{2t}{k}\right\} \oplus \mathcal{M}\left\{Bx_n, Tx_n, \frac{2t}{k}\right\} \geq \liminf_{n\to\infty} \mathcal{M}\left(Ay_n, Bx_n, \frac{2t}{k}\right)$.
Also, by remark 2.2, $\liminf_{n\to\infty} \mathcal{M}\left(Ay_n, Tx_n, \frac{4t}{k}\right) \oplus \mathcal{M}\left(Sy_n, Bx_n, \frac{4t}{k}\right) = \liminf_{n\to\infty} \mathcal{M}\left(Ay_n, Tx_n, \frac{4t}{k}\right) \oplus 1$
$$\geq \liminf_{n\to\infty} \mathcal{M}\left(Ay_n, Tx_n, \frac{2t}{k}\right),$$

hence letting $n\to\infty$, in inequality (2.3), we get,
$$\liminf_{n\to\infty} \mathcal{M}(Ay_n, z, t) = \mathcal{M}\left(\liminf_{n\to\infty} (Ay_n, z, t)\right) = \liminf_{n\to\infty} \mathcal{M}(Ay_n, Bx_n, t)$$

$$\geq \varphi \liminf_{n\to\infty} \mathcal{M}\left(Bx_n, Tx_n, \frac{2t}{k}\right), \liminf_{n\to\infty}\left\{\mathcal{M}\left(Ay_n, Bx_n, \frac{2t}{k}\right) \oplus \mathcal{M}\left(Bx_n, Tx_n, \frac{2t}{k}\right)\right\},$$
$$\liminf_{n\to\infty}\left\{\mathcal{M}\left(Ay_n, Tx_n, \frac{4t}{k}\right) \oplus 1\right\} \geq$$
$$\varphi\left(1, \liminf_{n\to\infty} \mathcal{M}\left(Ay_n, Bx_n, \frac{2t}{k}\right), \liminf_{n\to\infty} \mathcal{M}\left(Ay_n, Tx_n, \frac{2t}{k}\right)\right)$$
$$\geq \varphi\left(\liminf_{n\to\infty} \mathcal{M}\left(Ay_n, Bx_n, \frac{2t}{k}\right), \liminf_{n\to\infty} \mathcal{M}\left(Ay_n, Bx_n, \frac{2t}{k}\right), \liminf_{n\to\infty} \mathcal{M}\left(Ay_n, Tx_n, \frac{2t}{k}\right)\right)$$
$$= \varphi\left\{\mathcal{M}\left(\liminf_{n\to\infty} Ay_n, z, \frac{2t}{k}\right), \mathcal{M}\left(\liminf_{n\to\infty} Ay_n, z, \frac{2t}{k}\right), \mathcal{M}\left(\liminf_{n\to\infty} Ay_n, z, \frac{2t}{k}\right)\right\}$$
$$\geq \mathcal{M}\left(\liminf_{n\to\infty} Ay_n, z, \frac{2t}{k}\right)$$
$$\vdots$$
$$\geq \mathcal{M}\left(\liminf_{n\to\infty} Ay_n, z, \left(\frac{2}{k}\right)^n t\right) \to 1 .$$

Similarly, $\limsup_{n\to\infty} \mathcal{M}(Ay_n, z, t) = \mathcal{M}\left(\limsup_{n\to\infty} Ay_n, z, t\right) = 1$, hence, $\lim_{n\to\infty}\mathcal{M}(Ay_n, z, t) = 1$.

Assume that S(X) is a closed subset of X. Then, There exists u∈X s.t Su =z using (2.2), we get

$$\mathcal{M}(Au, Bx_n, t) \geq \varphi(\mathcal{M}\left(Su, Tx_n, \frac{2t}{k}\right), \mathcal{M}\left(Au, Su, \frac{2t}{k}\right) \oplus \mathcal{M}\left(Bx_n, Tx_n, \frac{2t}{k}\right),$$
$$\mathcal{M}\left(Au, Tx_n, \frac{4t}{k}\right) \oplus \mathcal{M}\left(Su, Bx_n, \frac{4t}{k}\right))$$

$$= \varphi\begin{pmatrix} \mathcal{M}\left(z, Tx_n, \frac{2t}{k}\right), \mathcal{M}\left(Au, z, \frac{2t}{k}\right) \oplus \mathcal{M}\left(Bx_n, Tx_n, \frac{2t}{k}\right), \\ \mathcal{M}\left(Au, Tx_n, \frac{4t}{k}\right) \oplus \mathcal{M}\left(z, Bx_n, \frac{4t}{k}\right) \end{pmatrix} \to (2.4).$$

In addition, it is easy to verify that

$$\liminf_{n\to\infty} \mathcal{M}\left(Au, Su, \frac{2t}{k}\right) \oplus \mathcal{M}\left(Bx_n, Tx_n, \frac{2t}{k}\right) \geq \mathcal{M}\left(Au, Su, \frac{2t}{k}\right) \to (2.5).$$

In fact, for all $\in \in \left(0, \frac{2t}{k}\right)$, we have

$$\mathcal{M}\left(Au, Su, \frac{2t}{k}\right) \oplus \mathcal{M}\left(Bx_n, Tx_n, \frac{2t}{k}\right) \geq \min\left\{\mathcal{M}\left(Au, Su, \frac{2t}{k} - \in\right), \mathcal{M}(Bx_n, Tx_n, \in)\right\}$$

Since $\lim_{n\to\infty} Bx_n = \lim_{n\to\infty} Tx_n = Su$, the above inequality implies that,

$$\liminf_{n\to\infty}\left(\mathcal{M}\left(Au, Su, \frac{2t}{k}\right) \oplus \mathcal{M}\left(Bx_n, Tx_n, \frac{2t}{k}\right) \geq \mathcal{M}\left(Au, Su, \frac{2t}{k} - \in\right)\right)$$

Letting $\in \to 0$, in the above inequality, we get (2.5). Also by remark (2.2), we get

$$\liminf_{n\to\infty}\left(\mathcal{M}\left(Au, Tx_n, \frac{4t}{k}\right) \oplus \mathcal{M}\left(Su, Bx_n, \frac{4t}{k}\right)\right) = \liminf_{n\to\infty} \mathcal{M}\left(Au, Tx_n, \frac{4t}{k}\right) \oplus 1$$
$$\geq \liminf_{n\to\infty} \mathcal{M}\left(Au, Tx_n, \frac{2t}{k}\right)$$
$$= \mathcal{M}\left(Au, z, \frac{2t}{k}\right)$$

So, letting $n \to \infty$, in inequality (2.4), we get

$$\mathcal{M}(Au, z, t) \geq \varphi\left(1, \mathcal{M}\left(Au, z, \frac{2t}{k}\right), \mathcal{M}\left(Au, z, \frac{2t}{k}\right)\right)$$
$$\geq \varphi\left(\mathcal{M}\left(Au, z, \frac{2t}{k}\right), \mathcal{M}\left(Au, z, \frac{2t}{k}\right), \mathcal{M}\left(Au, z, \frac{2t}{k}\right)\right)$$
$$\geq \mathcal{M}\left(Au, z, \frac{2t}{k}\right)$$
$$\vdots$$
$$\geq \mathcal{M}\left(Au, z, \left(\frac{2}{k}\right)^n t\right) \to 1.$$

Hence, $\mathcal{M}(Au, z, t) = 1$.

That is, Au= Su= z. Since, A(x) ⊆ T(x), There exists v∈X s.t z = Tv. Using (2.2), and Remark (2.2), we have $\mathcal{M}(z, Bv, t) = \mathcal{M}(Au, Bv, t)$

$$\geq \varphi\left(\mathcal{M}\left(Su, Tv, \frac{2t}{k}\right)\right), \mathcal{M}\left(Au, Su, \frac{2t}{k}\right) \oplus \mathcal{M}\left(Bv, Tv, \frac{2}{k}t\right),$$
$$\mathcal{M}\left(Au, Tv, \frac{4t}{k}\right) \oplus \mathcal{M}\left(Su, Bv, \frac{4t}{k}\right))$$
$$= \varphi\left(1, 1 \oplus \mathcal{M}\left(Bv, z, \frac{2t}{k}\right), 1 \oplus \mathcal{M}\left(z, Bv, \frac{4t}{k}\right)\right)$$
$$\geq \varphi\left(\mathcal{M}\left(Bv, z, \frac{2t}{k}\right), \mathcal{M}\left(Bv, z, \frac{2t}{k}\right), \mathcal{M}\left(z, Bv, \frac{2t}{k}\right)\right)$$

$$\geq \mathcal{M}\left(\mathrm{Bv}, \mathrm{z}, \frac{2\mathrm{t}}{\mathrm{k}}\right)$$
$$\vdots$$
$$\geq \mathcal{M}\left(\mathrm{Bv}, \mathrm{z}, \left(\frac{2}{\mathrm{k}}\right)^{\mathrm{n}} \mathrm{t}\right) \to 1.$$

Hence z = Bv = Tv.
Since the pairs (A, S) and (B, T) are weakly compatible, we obtain Az = Sz and Bz =Tz using the inequality (2.2), we have

$$\begin{aligned}
\mathcal{M}(\mathrm{Az}, \mathrm{z}, \mathrm{t}) &= \mathcal{M}(\mathrm{Az}, \mathrm{Bv}, \mathrm{t}) \\
&\geq \varphi\begin{pmatrix} \mathcal{M}\left(\mathrm{Sz}, \mathrm{Tv}, \frac{2\mathrm{t}}{\mathrm{k}}\right), \mathcal{M}\left(\mathrm{Az}, \mathrm{Sz}, \frac{2\mathrm{t}}{\mathrm{k}}\right) \oplus \mathcal{M}\left(\mathrm{Bv}, \mathrm{Tv}, \frac{2\mathrm{t}}{\mathrm{k}}\right), \\ \mathcal{M}\left(\mathrm{Az}, \mathrm{Tv}, \frac{4\mathrm{t}}{\mathrm{k}}\right) \oplus \mathcal{M}\left(\mathrm{Sz}, \mathrm{Bv}, \frac{4\mathrm{t}}{\mathrm{k}}\right) \end{pmatrix} \\
&= \varphi\left(\mathcal{M}\left(\mathrm{Az}, \mathrm{z}, \frac{2\mathrm{t}}{\mathrm{k}}\right), 1 \oplus 1, \mathcal{M}\left(\mathrm{Az}, \mathrm{z}, \frac{4\mathrm{t}}{\mathrm{k}}\right) \oplus \mathcal{M}\left(\mathrm{Az}, \mathrm{z}, \frac{4\mathrm{t}}{\mathrm{k}}\right)\right) \\
&\geq \varphi\left(\mathcal{M}\left(\mathrm{Az}, \mathrm{z}, \frac{2\mathrm{t}}{\mathrm{k}}\right), \mathcal{M}\left(\mathrm{Az}, \mathrm{z}, \frac{2\mathrm{t}}{\mathrm{k}}\right), \mathcal{M}\left(\mathrm{Az}, \mathrm{z}, \frac{2\mathrm{t}}{\mathrm{k}}\right)\right) \\
&\geq \mathcal{M}\left(\mathrm{Az}, \mathrm{z}, \frac{2\mathrm{t}}{\mathrm{k}}\right) \\
&\vdots \\
&\geq \mathcal{M}\left(\mathrm{Az}, \mathrm{z}, \left(\frac{2}{\mathrm{k}}\right)^{\mathrm{n}} \mathrm{t}\right) \to 1.
\end{aligned}$$

Then Az = Sz = z.
Similarly, we can prove that z = Bz =Tz. Therefore z is a common fixed point of A, B, S and T.
Now, we prove the **uniqueness:**
Let if possible w ≠z be another common fixed point of A, B, S and T. Then by inequality (2.2), we have

$$\begin{aligned}
\mathcal{M}(\mathrm{z}, \mathrm{w}, \mathrm{t}) &= \mathcal{M}(\mathrm{Az}, \mathrm{Bw}, \mathrm{t}) \\
&\geq \varphi\begin{pmatrix} \mathcal{M}\left(\mathrm{Sz}, \mathrm{Tw}, \frac{2\mathrm{t}}{\mathrm{k}}\right), \mathcal{M}\left(\mathrm{Az}, \mathrm{Sz}, \frac{2\mathrm{t}}{\mathrm{k}}\right) \oplus \mathcal{M}\left(\mathrm{Bw}, \mathrm{Tw}, \frac{2\mathrm{t}}{\mathrm{k}}\right), \\ \mathcal{M}\left(\mathrm{Az}, \mathrm{Tw}, \frac{4\mathrm{t}}{\mathrm{k}}\right) \oplus \mathcal{M}\left(\mathrm{Sz}, \mathrm{Bw}, \frac{4\mathrm{t}}{\mathrm{k}}\right) \end{pmatrix} \\
&\geq \varphi\left(\mathcal{M}\left(\mathrm{z}, \mathrm{w}, \frac{2\mathrm{t}}{\mathrm{k}}\right), 1 \oplus 1, \mathcal{M}\left(\mathrm{z}, \mathrm{w}, \frac{4\mathrm{t}}{\mathrm{k}}\right) \oplus \mathcal{M}\left(\mathrm{z}, \mathrm{w}, \frac{4\mathrm{t}}{\mathrm{k}}\right)\right) \\
&\geq \varphi\left(\mathcal{M}\left(\mathrm{z}, \mathrm{w}, \frac{2\mathrm{t}}{\mathrm{k}}\right), \mathcal{M}\left(\mathrm{z}, \mathrm{w}, \frac{2\mathrm{t}}{\mathrm{k}}\right), \mathcal{M}\left(\mathrm{z}, \mathrm{w}, \frac{2\mathrm{t}}{\mathrm{k}}\right)\right) \\
&\geq \mathcal{M}\left(\mathrm{z}, \mathrm{w}, \frac{2\mathrm{t}}{\mathrm{k}}\right) \\
&\vdots \\
&\geq \mathcal{M}\left(\mathrm{z}, \mathrm{w}, \left(\frac{2}{\mathrm{k}}\right)^{\mathrm{n}} \mathrm{t}\right) \to 1.
\end{aligned}$$

which is a contradiction. Hence w = z is a unique common fixed point of A, B, S and T.

Remark: 2.3:
Putting B =A, and T= S in the above theorem, we get the following corollary 2.6.

Corollary 2.4:
Let A and S be mappings from a fuzzy metric space (X, $\mathcal{M}$, *) into itself satisfying the following condition:

(i) $A(x) \subseteq S(x)$

(ii) $$\mathcal{M}(\mathrm{Ax}, \mathrm{Ay}, \mathrm{t}) \geq \varphi\begin{pmatrix} \mathcal{M}\left(\mathrm{Sx}, \mathrm{Sy}, \frac{2\mathrm{t}}{\mathrm{k}}\right), \mathcal{M}\left(\mathrm{AX}, \mathrm{Sx}, \frac{2\mathrm{t}}{\mathrm{k}}\right) \oplus \mathcal{M}\left(\mathrm{Ay}, \mathrm{Sy}, \frac{2\mathrm{t}}{\mathrm{k}}\right), \\ \mathcal{M}\left(\mathrm{Ax}, \mathrm{Sy}, \frac{4\mathrm{t}}{\mathrm{k}}\right) \oplus \mathcal{M}\left(\mathrm{Sx}, \mathrm{Ay}, \frac{4\mathrm{t}}{\mathrm{k}}\right) \end{pmatrix}$$

for all x, y∈X, and t>0, Where $0 \leq k < 2$. Suppose that the pair (A, S) satisfies the property (E-A), (A,S) is weakly compatible and one of A(x) and S(x) is a complete subspace of X. Then A and S have a unique common fixed point in X.

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