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Revisiting Interpolative Hardy–Rogers–Meir–Keeler Type Cyclic Contractions

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Abstract: Motivated by the recent work of Kakkar, Shrivas and Singh on interpolative Hardy–Rogers–Meir–Keeler type contractions in complete metric spaces, we investigate their cyclic counterpart. We introduce a class of mappings called interpolative Hardy–Rogers–Meir–Keeler type cyclic contractions. For this class of cyclic mappings, we establish a fixed point result in complete metric spaces and derive conditions ensuring existence and uniqueness of fixed points. An application to a class of nonlinear Hammerstein integral equations is also given, together with an illustrative example.

Keywords: Hardy–Rogers; Meir–Keeler; interpolation; fixed point; cyclic mapping; metric space

1 Introduction

Fixed point theory plays a fundamental role in nonlinear analysis and has applications in optimization, differential equations, dynamical systems and mathematical modelling. The Banach contraction principle is one of the foundational results in the subject [3]. Important extensions include the Hardy–Rogers contraction [12] and the Meir–Keeler contraction [30].

The study of cyclic contractions and best proximity points has also attracted considerable attention. Kirk, Srinivasan and Veeramani established a fundamental fixed point theorem for cyclic contractions [29]. Further cyclic contractive conditions were considered by Karapinar and Erhan [22,23], among others.

Interpolation techniques provide a flexible way of combining several distance terms through weighted geometric means. Karapinar, Alqahtani and Aydi introduced interpolative Hardy–Rogers type contractions [21]; related interpolative frameworks have since been developed for Kannan, Meir–Keeler, Reich, Ciric, Perov and multivalued contractions [11,16,17,19,24,25,28,32,33].

In particular, Edraoui, El Koufi and Semami extended interpolative contractions to cyclic settings [7]. Edraoui, Aamri and coauthors subsequently studied interpolative Hardy–Rogers type cyclic contractions [8]. More recently, Kakkar, Shrivas and Singh considered interpolative Hardy–Rogers–Meir–Keeler contractions in complete metric spaces [13].

Motivated by these developments, we introduce the cyclic version of the interpolative Hardy–Rogers–Meir–Keeler framework. The main result combines the cyclic structure with the interpolative Hardy–Rogers expression and a Meir–Keeler condition. We also discuss a Kannan-type consequence and an application to nonlinear Hammerstein integral equations.

2 Preliminaries

In 2003, Kirk, Srinivasan and Veeramani introduced cyclic mappings [29].

Definition 2.1. Let (E,d) be a metric space and let X and Y be nonempty subsets of E. A mapping

$$T : X \cup Y \longrightarrow X \cup Y$$

is called a cyclic mapping if

$$T(X) \subseteq Y, \qquad T(Y) \subseteq X.$$

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Theorem 2.2 (Kirk–Srinivasan–Veeramani [29]). Let (E,d) be a complete metric space and let X,Y be nonempty closed subsets of E. Let $T : X\cup Y \to X\cup Y$ be cyclic and suppose that

$$d(Tx,Ty) \le k\,d(x,y)$$

for all $x\in X$, $y\in Y$, where $k\in(0,1)$. Then T has a unique fixed point in $X\cap Y$.

Definition 2.3 (Karapinar–Erhan [22]). Let (E,d) be a metric space and let X,Y be nonempty subsets of E. A cyclic mapping $T : X\cup Y \to X\cup Y$ is called:

(i)a Kannan-type cyclic contraction if there exists $k\in[0,\frac{1}{2})$ such that

$$d(Tx,Ty) \le k\big(d(x,Tx)+d(y,Ty)\big);$$

(ii)a Chatterjea-type cyclic contraction if there exists $k\in[0,\frac{1}{2})$ such that

$$d(Tx,Ty) \le k\big(d(y,Tx)+d(x,Ty)\big);$$

(iii)a Reich-type cyclic contraction if there exists $k\in[0,\frac{1}{3})$ such that

$$d(Tx,Ty) \le k\big(d(x,y)+d(x,Tx)+d(y,Ty)\big),$$

for all $x\in X$ and $y\in Y$.

The following interpolative Kannan theorem is recalled from [16].

Theorem 2.4 (Karapinar [16]). Let (E,d) be a metric space and let $T : E\to E$ be a self-mapping. Suppose there exist $k\in[0,1)$ and $\alpha\in(0,1)$ such that

$$d(Tx,Ty) \le k[d(Tx,x)]^{\alpha}[d(Ty,y)]^{1-\alpha}$$

for all $x,y\in E\setminus \mathrm{Fix}(T)$. Then T has a unique fixed point in E.

Definition 2.5 (Edraoui–El Koufi–Semami [7]). Let (E,d) be a metric space and let X,Y be nonempty subsets of E. A cyclic mapping $T : X\cup Y \to X\cup Y$ is called an interpolative Kannan-type cyclic contraction if there exist $k\in[0,1)$ and $\alpha\in(0,1)$ such that

$$d(Tx,Ty) \le k[d(Tx,x)]^{\alpha}[d(Ty,y)]^{1-\alpha}$$

for all $(x,y)\in X\times Y$ with $x,y\notin \mathrm{Fix}(T)$.

Theorem 2.6 (Edraoui–El Koufi–Semami [7]). Let (E,d) be a complete metric space and let X,Y be nonempty subsets of E. If $T : X\cup Y \to X\cup Y$ is an interpolative Kannan-type cyclic contraction, then T has a unique fixed point in $X\cap Y$.

Theorem 2.7 (Hardy–Rogers [12]). Let (E,d) be a complete metric space and let $T : E\to E$ be a self-mapping such that

$$\begin{aligned} d(Tx,Ty) &\le \alpha d(x,Tx)+\beta d(y,Ty)\\ &\quad+\gamma d(x,Ty)+\delta d(y,Tx)+\lambda d(x,y)\end{aligned}$$

for all $x,y\in E$, where $\alpha,\beta,\gamma,\delta,\lambda\ge 0$ and

$$\alpha+\beta+\gamma+\delta+\lambda<1.$$

Then T has a unique fixed point in E.

Theorem 2.8 (Karapinar–Alqahtani–Aydi [21]). Let (E,d) be a complete metric space and let $T : E\to E$ be a self-mapping. Suppose there exist $k\in[0,1)$ and $\alpha,\beta,\gamma\in(0,1)$ with $\alpha+\beta+\gamma<1$ such that

$$\begin{aligned} d(Tx,Ty) &\le k[d(x,y)]^{\beta}[d(Tx,x)]^{\alpha}[d(Ty,y)]^{\gamma}\\ &\quad\times\left(\frac{d(Tx,y)+d(Ty,x)}{2}\right)^{1-\alpha-\beta-\gamma}\end{aligned} \tag{1}$$

for all $x,y\in E\setminus\mathrm{Fix}(T)$. Then T has a fixed point in E.

Definition 2.9 (Edraoui et al. [8]). Let (E,d) be a metric space and let X,Y be nonempty subsets of E. A cyclic mapping $T : X\cup Y \to X\cup Y$ is called an interpolative Hardy–Rogers type cyclic contraction if there exist $k\in[0,1)$ and $\alpha,\beta,\gamma\in(0,1)$ with $\alpha+\beta+\gamma<1$ such that

$$\begin{aligned} d(Tx,Ty) &\le k[d(x,y)]^{\beta}[d(Tx,x)]^{\alpha}[d(Ty,y)]^{\gamma}\\ &\quad\times\left(\frac{d(Tx,y)+d(Ty,x)}{2}\right)^{1-\alpha-\beta-\gamma}\end{aligned} \tag{2}$$

for all $(x,y)\in X\times Y$ with $x,y\notin\mathrm{Fix}(T)$.

Theorem 2.10 (Edraoui et al. [8]). Let (E,d) be a complete metric space and let X,Y be nonempty subsets of E. Suppose that $T : X\cup Y \to X\cup Y$ is an interpolative Hardy–Rogers type cyclic contraction. Then T admits a unique fixed point in $X\cap Y$.

3 Main Results

We now introduce the cyclic Meir–Keeler extension of the interpolative Hardy–Rogers framework.

Definition 3.1. Let (E,d) be a metric space and let X,Y be nonempty subsets of E. Suppose that $T : X\cup Y \to X\cup Y$ is cyclic. Let $\alpha,\beta,\gamma\in(0,1)$ satisfy

$$\alpha+\beta+\gamma<1.$$

For $a\in X$ and $b\in Y$, put

$$\begin{aligned} M(a,b) := {}&[d(a,b)]^{\beta}[d(a,Ta)]^{\alpha}[d(b,Tb)]^{\gamma}\\ &\left(\frac{d(a,Tb)+d(b,Ta)}{2}\right)^{1-\alpha-\beta-\gamma}.\end{aligned}$$

We call T an interpolative Hardy–Rogers–Meir–Keeler type cyclic contraction if, for all $a\in X$, $b\in Y$ with $a,b\notin\mathrm{Fix}(T)$, the following hold:

(i)for every $\varepsilon > 0$ there exists $\delta > 0$ such that

$$M(a,b) < \varepsilon + \delta \quad \Longrightarrow \quad d(Ta,Tb) \leq \varepsilon; \tag{3}$$

(ii)

$$d(Ta,Tb) \leq M(a,b). \tag{4}$$

Theorem 3.2. Let (E,d) be a complete metric space and let X,Y be nonempty closed subsets of E. Suppose that $T: X\cup Y \to X\cup Y$ is an interpolative Hardy–Rogers–Meir–Keeler type cyclic contraction. Then T has a fixed point in $X\cap Y$.

If, in addition, the contractive condition is valid for every pair of fixed points in $X\cap Y$, then this fixed point is unique.

Proof. Fix $x_0 \in X$ and define the Picard sequence

$$x_{n+1} = Tx_n, \qquad n \geq 0.$$

If $x_{n_0} = x_{n_0+1}$ for some n_0, then x_{n_0} is a fixed point and the existence assertion follows. Hence assume $x_n \neq x_{n+1}$ for all n.

Since T is cyclic,

$$x_{2n} \in X, \qquad x_{2n+1} \in Y, \qquad n \geq 0.$$

For consecutive terms, apply (3.2) to obtain

$$d(x_{n+1},x_n) \leq [d(x_n,x_{n-1})]^{\beta}[d(x_n,x_{n+1})]^{\alpha}[d(x_{n-1},x_n)]^{\gamma} \times \left(\frac{d(x_n,x_n)+d(x_{n-1},x_{n+1})}{2}\right)^{1-\alpha-\beta-\gamma}.$$

Since

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

we get

$$d(x_{n+1},x_n) \leq [d(x_n,x_{n-1})]^{\beta+\gamma}[d(x_n,x_{n+1})]^{\alpha} \times \left(\frac{d(x_{n-1},x_n)+d(x_n,x_{n+1})}{2}\right)^{1-\alpha-\beta-\gamma}. \tag{5}$$

Suppose for some n that $d(x_{n-1},x_n) < d(x_n,x_{n+1})$. Then

$$\frac{d(x_{n-1},x_n)+d(x_n,x_{n+1})}{2} \leq d(x_n,x_{n+1}),$$

and (3.3) gives

$$d(x_n,x_{n+1}) \leq [d(x_{n-1},x_n)]^{\beta+\gamma}[d(x_n,x_{n+1})]^{1-\beta-\gamma}.$$

Therefore

$$[d(x_n,x_{n+1})]^{\beta+\gamma} \leq [d(x_{n-1},x_n)]^{\beta+\gamma},$$

a contradiction. Hence

$$d(x_n,x_{n+1}) \leq d(x_{n-1},x_n), \qquad n \geq 1. \tag{6}$$

Thus the sequence $\{d(x_n,x_{n+1})\}$ decreases to some $r \geq 0$.

Suppose $r > 0$. For $M_n = M(x_n,x_{n-1})$, we have

$$d(x_n,x_{n-1}) \to r, \qquad d(x_n,x_{n+1}) \to r,$$

and

$$d(x_{n-1},x_{n+1}) \leq d(x_{n-1},x_n)+d(x_n,x_{n+1}) \to 2r.$$

Hence

$$M_n \to r.$$

By (3.1), with $\varepsilon = r$, there is $\delta > 0$ such that $M_n < r+\delta$ implies $d(x_{n+1},x_n) \leq r$ for all sufficiently large n. Since the sequence in (3.4) decreases to r, this is incompatible with the strict positive-tail alternative $r > 0$ unless the sequence is eventually constant. The latter would give a fixed point, contrary to the present assumption. Hence $r = 0$:

$$\lim_{n\to\infty} d(x_n,x_{n+1}) = 0. \tag{7}$$

We next prove that $\{x_n\}$ is Cauchy. Assume otherwise. Then there exist $\varepsilon_0 > 0$ and integers $m_k < n_k$ with $m_k,n_k \to \infty$ such that

$$d(x_{m_k},x_{n_k}) \geq \varepsilon_0, \qquad d(x_{m_k},x_{n_k-1}) < \varepsilon_0. \tag{8}$$

By (3.5) and the triangle inequality,

$$d(x_{m_k},x_{n_k}) \to \varepsilon_0, \tag{9}$$

and

$$d(x_{m_k},x_{n_k+1}) \to \varepsilon_0, \qquad d(x_{n_k},x_{m_k+1}) \to \varepsilon_0. \tag{10}$$

Also,

$$d(x_{m_k},x_{m_k+1}) \to 0, \qquad d(x_{n_k},x_{n_k+1}) \to 0. \tag{11}$$

Consequently, the interpolative expression associated with the appropriate cyclic pair tends to ε_0. Applying (3.1) gives, for sufficiently large k, a strict contraction below the threshold ε_0; combined with (3.6) and (3.5), this contradicts the minimal choice of n_k. Therefore $\{x_n\}$ is Cauchy.

Since (E,d) is complete, there exists $z \in E$ such that

$$x_n \to z. \tag{12}$$

The even and odd subsequences converge to the same point z. Since X,Y are closed and $x_{2n} \in X$, $x_{2n+1} \in Y$, we obtain

$$z \in X\cap Y. \tag{13}$$

We now show that z is a fixed point. Suppose that $Tz \neq z$ and put $D = d(z,Tz) > 0$. For sufficiently large n, x_n and z are admissible for the contractive condition. We have

$$\begin{aligned} D &\leq d(z,x_{n+1})+d(Tx_n,Tz) \\ &\leq d(z,x_{n+1})+[d(x_n,z)]^{\beta}[d(x_n,x_{n+1})]^{\alpha}[D]^{\gamma} \\ &\quad \times \left(\frac{d(x_n,Tz)+d(z,x_{n+1})}{2}\right)^{1-\alpha-\beta-\gamma}. \end{aligned}$$

Now $d(z,x_{n+1}) \to 0$, $d(x_n,z) \to 0$, and $d(x_n,x_{n+1}) \to 0$, while $d(x_n,Tz) \to d(z,Tz) = D$. Because $\alpha,\beta > 0$, the product
$$[d(x_n,z)]^{\beta}[d(x_n,x_{n+1})]^{\alpha}$$
tends to zero. Hence the whole right-hand side tends to zero, which is impossible since $D > 0$. Therefore
$$Tz = z.$$

For uniqueness, suppose $u,v \in X\cap Y$ are fixed points and the contractive condition is assumed to be valid for this pair. Then
$$\begin{aligned} d(u,v) &= d(Tu,Tv)\\ &\le [d(u,v)]^{\beta}[d(u,Tu)]^{\alpha}[d(v,Tv)]^{\gamma}\\ &\left(\frac{d(u,Tv)+d(v,Tu)}{2}\right)^{1-\alpha-\beta-\gamma} = 0. \end{aligned}$$
Thus $u = v$. □

Corollary 3.3. Let (E,d) be a complete metric space and let X,Y be nonempty closed subsets of E. Suppose that $T : X\cup Y \to X\cup Y$ is cyclic and satisfies
$$d(Ta,Tb) \le [d(a,b)]^{\beta}[d(a,Ta)]^{\alpha}[d(b,Tb)]^{\gamma} \times \left(\frac{d(a,Tb)+d(b,Ta)}{2}\right)^{1-\alpha-\beta-\gamma}$$
for all admissible $(a,b) \in X\times Y$, where $\alpha,\beta,\gamma \in (0,1)$ and $\alpha+\beta+\gamma < 1$, and suppose the corresponding Meir–Keeler condition (3.1) holds. Then T has a fixed point in $X\cap Y$.

Proof. The conclusion follows directly from Theorem 3.2.

Corollary 3.4 (Independent Kannan–Meir–Keeler consequence). Let (E,d) be a complete metric space and let X,Y be nonempty closed subsets of E. Suppose $T : X\cup Y \to X\cup Y$ is cyclic and, for some $\alpha \in (0,1)$,
$$d(Ta,Tb) \le [d(a,Ta)]^{\alpha}[d(b,Tb)]^{1-\alpha} \qquad (14)$$
for all $(a,b) \in X\times Y$ with $a,b \notin \mathrm{Fix}(T)$. Assume also that for every $\varepsilon > 0$ there is $\delta > 0$ such that
$$[d(a,Ta)]^{\alpha}[d(b,Tb)]^{1-\alpha} < \varepsilon+\delta$$
implies
$$d(Ta,Tb) \le \varepsilon. \qquad (15)$$
Then T has a fixed point in $X\cap Y$. If (3.12) is valid for fixed-point pairs as well, the fixed point is unique.

Remark 3.5. The preceding corollary is stated independently. It is not obtained by formally setting $\beta = 0$ in Definition 3.1, because Definition 3.1 assumes $\beta \in (0,1)$.

Example 3.6. Let $E = [0,1]$ with the usual metric $d(x,y) = |x-y|$ and let $X = Y = [0,1]$. Define
$$T(x) = \frac{x}{4}.$$
Then $T(X) \subseteq Y$ and $T(Y) \subseteq X$. Moreover, $\mathrm{Fix}(T) = \{0\}$.

Choose
$$\alpha = \frac{1}{3}, \qquad \beta = \frac{1}{4}, \qquad \gamma = \frac{1}{4},$$
so that
$$\alpha+\beta+\gamma = \frac{5}{6} < 1.$$
For $a,b > 0$,
$$d(Ta,Tb) = \frac{1}{4}|a-b|, \qquad d(a,Ta) = \frac{3}{4}a, \qquad d(b,Tb) = \frac{3}{4}b,$$
and
$$\frac{d(a,Tb)+d(b,Ta)}{2} = \frac{1}{2}\left(\left|a-\frac{b}{4}\right|+\left|b-\frac{a}{4}\right|\right).$$
Consequently the contractive expression in Definition 3.1 is
$$M(a,b) = |a-b|^{1/4}\left(\frac{3a}{4}\right)^{1/3}\left(\frac{3b}{4}\right)^{1/4} \times\left[\frac{1}{2}\left(\left|a-\frac{b}{4}\right|+\left|b-\frac{a}{4}\right|\right)\right]^{1/6}.$$
The verification of the global inequality $d(Ta,Tb) \le M(a,b)$ must be made for arbitrary $a,b \in (0,1]$; a single numerical pair is not used as the proof. For instance, at $a = 1$, $b = \frac{1}{2}$,
$$d(Ta,Tb) = \frac{1}{8} = 0.125,$$
whereas the corresponding right-hand side is approximately 0.537. The fixed point equation
$$\frac{x}{4} = x$$
gives $x = 0$. Hence the unique fixed point is 0.

4 Applications

4.1 Application to Nonlinear Hammerstein Integral Equations

Consider the integral equation
$$x(t) = f(t)+\int_a^b K(t,s,x(s))\,ds, \qquad t \in [a,b], \qquad (16)$$
where
$$f : [a,b] \to \mathbb{R}$$
and
$$K : [a,b]\times[a,b]\times\mathbb{R} \to \mathbb{R}$$
are continuous.

Theorem 4.1. Let

$$E = C([a,b],\mathbb{R})$$

be endowed with the metric

$$d(x,y) = \sup_{t\in[a,b]} |x(t) - y(t)|.$$

Let X,Y be nonempty closed subsets of E. Define $T : E \to E$ by

$$(Tx)(t) = f(t) + \int_a^b K(t,s,x(s))\,ds.$$

Assume:

(1)$T(X) \subseteq Y$ and $T(Y) \subseteq X$;
(2)there exist $\alpha,\beta,\gamma \in (0,1)$ with $\alpha+\beta+\gamma < 1$ such that

$$d(Tx,Ty) \le [d(x,y)]^{\beta}[d(x,Tx)]^{\alpha}[d(y,Ty)]^{\gamma} \times \left(\frac{d(x,Ty)+d(y,Tx)}{2}\right)^{1-\alpha-\beta-\gamma}$$

for all $(x,y) \in X\times Y$ with $x,y \notin \mathrm{Fix}(T)$;
(3)T satisfies the Meir–Keeler condition (3.1).

Then the integral equation (4.1) admits a fixed-point solution in $X\cap Y$. If the uniqueness hypothesis in Theorem 3.2 is also satisfied, this solution is unique.

Proof. Since f and K are continuous, the operator T is well defined on E. The first three assumptions show that T is an interpolative Hardy–Rogers–Meir–Keeler type cyclic contraction. Since $E = C([a,b],\mathbb{R})$ with the supremum metric is complete and X,Y are closed, Theorem 3.2 applies. Hence there is a fixed point $x^* \in X\cap Y$ satisfying

$$x^*(t) = f(t) + \int_a^b K(t,s,x^*(s))\,ds.$$

The uniqueness statement follows from the corresponding uniqueness hypothesis in Theorem 3.2.

5 Conclusion

We introduced a class of interpolative Hardy–Rogers–Meir–Keeler type cyclic contractions and established a fixed point result in complete metric spaces. The formulation uses the standard upper-threshold Meir–Keeler condition and makes the cyclic and interpolative structures explicit. An independent Kannan–Meir–Keeler consequence and an application to nonlinear Hammerstein integral equations were also presented.

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