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FIXED POINTS AND FUZZY STABILITY OF QUADRATIC FUNCTIONAL EQUATIONS

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Abstract. Using the fixed point method, we prove the Hyers-Ulam stability of the following quadratic functional equations

$$\begin{aligned} & cf\left(\sum_{i=1}^{n} x_i\right) + \sum_{j=2}^{n} f\left(\sum_{i=1}^{n} x_i - (n+c-1)x_j\right) \\ & = (n+c-1)\left(f(x_1) + c\sum_{i=2}^{n} f(x_i) + \sum_{i<j,j=3}^{n}\left(\sum_{i=2}^{n-1} f(x_i - x_j)\right)\right), \end{aligned}$$

$$\begin{aligned} & f\left(\sum_{i=1}^{n} d_i x_i\right) + \sum_{1\le i<j\le n} d_i d_j f(x_i - x_j) \\ & \qquad = \left(\sum_{i=1}^{n} d_i\right)\left(\sum_{i=1}^{n} d_i f(x_i)\right) \end{aligned}$$

in fuzzy Banach spaces.

1. Introduction and preliminaries

Katsaras [19] defined a fuzzy norm on a vector space to construct a fuzzy vector topological structure on the space. Some mathematicians have defined fuzzy norms on a vector space from various points of view [12, 21, 41]. In particular, Bag and Samanta [2], following Cheng and Mordeson [7], gave an idea of fuzzy norm in such a manner that the corresponding fuzzy metric is of Kramosil and Michalek type [20]. They established a decomposition theorem of a fuzzy norm into a family of crisp norms and investigated some properties of fuzzy normed spaces [3].

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We use the definition of fuzzy normed spaces given in [2, 23, 24] to investigate a fuzzy version of the Hyers-Ulam stability for the above quadratic functional equations in the fuzzy normed vector space setting.

Definition 1.1. [2, 23, 24, 25] Let X be a real vector space. A function $N : X \times \mathbb{R} \to [0,1]$ is called a *fuzzy norm* on X if for all $x, y \in X$ and all $s, t \in \mathbb{R}$,

(N_1) $N(x,t) = 0$ for $t \leq 0$;

(N_2) $x = 0$ if and only if $N(x,t) = 1$ for all $t > 0$;

(N_3) $N(cx,t) = N(x, \frac{t}{|c|})$ if $c \neq 0$;

(N_4) $N(x+y, s+t) \geq \min\{N(x,s), N(y,t)\}$;

(N_5) $N(x,\cdot)$ is a non-decreasing function of $\mathbb{R}$ and $\lim_{t\to\infty} N(x,t) = 1$;

(N_6) for $x \neq 0$, $N(x,\cdot)$ is continuous on $\mathbb{R}$.

The pair (X,N) is called a *fuzzy normed vector space*.

The properties of fuzzy normed vector spaces and examples of fuzzy norms are given in [23].

Definition 1.2. [2, 23, 24, 25] Let (X,N) be a fuzzy normed vector space. A sequence $\{x_n\}$ in X is said to *be convergent* or *converge* if there exists an $x \in X$ such that $\lim_{n\to\infty} N(x_n - x, t) = 1$ for all $t > 0$. In this case, x is called the *limit* of the sequence $\{x_n\}$ and we denote it by $N\text{-}\lim_{n\to\infty} x_n = x$.

Definition 1.3. [2, 23, 24] Let (X,N) be a fuzzy normed vector space. A sequence $\{x_n\}$ in X is called *Cauchy* if for each $\varepsilon > 0$ and each $t > 0$ there exists an $n_0 \in \mathbb{N}$ such that for all $n \geq n_0$ and all $p > 0$, we have $N(x_{n+p} - x_n, t) > 1 - \varepsilon$.

It is well-known that every convergent sequence in a fuzzy normed vector space is Cauchy. If each Cauchy sequence is convergent, then the fuzzy norm is said to be *complete* and the fuzzy normed vector space is called a *fuzzy Banach space*.

We say that a mapping $f : X \to Y$ between fuzzy normed vector spaces X and Y is continuous at a point $x_0 \in X$ if for each sequence $\{x_n\}$ converging to x_0 in X, then the sequence $\{f(x_n)\}$ converges to $f(x_0)$. If $f : X \to Y$ is continuous at each $x \in X$, then $f : X \to Y$ is said to be *continuous* on X (see [3]).

The stability problem of functional equations was originated from a question of Ulam [40] concerning the stability of group homomorphisms. Hyers [15] gave a first affirmative partial answer to the question of Ulam for Banach spaces. Hyers' Theorem was generalized by Aoki [1] for additive mappings and by Th.M. Rassias [30] for linear mappings by considering an unbounded Cauchy difference. The paper of Th.M. Rassias [30] has provided a lot of influence in the development of what we call *Hyers-Ulam stability* or *Hyers-Ulam-Rassias stability* of functional equations. A generalization of the Th.M. Rassias theorem was obtained by Găvruta [14] by replacing the unbounded Cauchy difference by a general control function in the spirit of Th.M. Rassias' approach.

The functional equation

$$f(x+y)+f(x-y)=2f(x)+2f(y)$$

is called a *quadratic functional equation*. In particular, every solution of the quadratic functional equation is said to be a *quadratic function*. The Hyers-Ulam stability of the quadratic functional equation was proved by Skof [39] for mappings $f : X \to Y$, where X is a normed space and Y is a Banach space. Cholewa [8] noticed that the theorem of Skof is still true if the relevant domain X is replaced by an Abelian group. Czerwik [9] proved the Hyers-Ulam stability of the quadratic functional equation. The stability problems of several functional equations have been extensively investigated by a number of authors and there are many interesting results concerning this problem (see [10, 13, 16, 18], [31]–[38]).

Let X be a set. A function $d : X \times X \to [0, \infty]$ is called a *generalized metric* on X if d satisfies

(1) $d(x, y) = 0$ if and only if $x = y$;

(2) $d(x, y) = d(y, x)$ for all $x, y \in X$;

(3) $d(x, z) \le d(x, y) + d(y, z)$ for all $x, y, z \in X$.

We recall a fundamental result in fixed point theory.

Theorem 1.4. [4, 11] *Let (X, d) be a complete generalized metric space and let $J : X \to X$ be a strictly contractive mapping with Lipschitz constant $L < 1$. Then for each given element $x \in X$, either*

$$d(J^n x, J^{n+1}x) = \infty$$

for all nonnegative integers n or there exists a positive integer n_0 such that

(1) $d(J^n x, J^{n+1}x) < \infty, \qquad \forall n \ge n_0$;

(2) *the sequence $\{J^n x\}$ converges to a fixed point y^* of J;*

(3) *y^* is the unique fixed point of J in the set $Y = \{y \in X \mid d(J^{n_0}x, y) < \infty\}$;*

(4) $d(y, y^*) \le \frac{1}{1-L} d(y, Jy)$ *for all $y \in Y$.*

In 1996, G. Isac and Th.M. Rassias [17] were the first to provide applications of stability theory of functional equations for the proof of new fixed point theorems with applications. By using fixed point methods, the stability problems of several functional equations have been extensively investigated by a number of authors (see [5, 6, 26, 27, 28, 29]).

This paper is organized as follows: In Section 3, we prove the Hyers-Ulam stability of the quadratic functional equation

$$\begin{aligned} &cf\left(\sum_{i=1}^{n} x_i\right) + \sum_{j=2}^{n} f\left(\sum_{i=1}^{n} x_i - (n+c-1)x_j\right) \\ &= (n+c-1)\left(f(x_1) + c\sum_{i=2}^{n} f(x_i) + \sum_{i<j,j=3}^{n}\left(\sum_{i=2}^{n-1} f(x_i - x_j)\right)\right) \end{aligned} \tag{1.1}$$

in fuzzy Banach spaces by using the fixed point method. In Section 4, we prove the Hyers-Ulam stability of the quadratic functional equation

$$\begin{aligned} &f\left(\sum_{i=1}^{n} d_i x_i\right) + \sum_{1\le i<j\le n} d_i d_j f(x_i - x_j) \\ &= \left(\sum_{i=1}^{n} d_i\right)\left(\sum_{i=1}^{n} d_i f(x_i)\right) \end{aligned} \tag{1.2}$$

in fuzzy Banach spaces.

Throughout this paper, assume that X is a vector space and that (Y, N) is a fuzzy Banach space. Let n be a fixed integer greater than 1, and let $v := 2 - n - c > 1$ and $d := \sum_{i=1}^{n} d_i > 1$.

2. Hyers-Ulam stability of the quadratic functional equation (1.1) in fuzzy Banach spaces

For a given mapping $f : X \to Y$, consider the mapping $Pf : X^n \to Y$, defined by

$$\begin{aligned} Pf(x_1, x_2, \cdots, x_n) &= cf\left(\sum_{i=1}^{n} x_i\right) + \sum_{j=2}^{n} f\left(\sum_{i=1}^{n} x_i - (n+c-1)x_j\right) \\ &-(n+c-1)\left(f(x_1) + c\sum_{i=2}^{n} f(x_i) + \sum_{i<j,j=3}^{n}\left(\sum_{i=2}^{n-1} f(x_i - x_j)\right)\right) \end{aligned}$$

for all $x_1, \cdots, x_n \in X$.

Using the fixed point method, we prove the Hyers-Ulam stability of the quadratic functional equation $Pf(x_1, \cdots, x_n) = 0$ in fuzzy Banach spaces.

THEOREM 2.1. *Let* $\varphi : X^n \to [0, \infty)$ *and* $\psi(x) := \varphi(0, x, \underbrace{0, \cdots, 0}_{n-2 \text{ times}})$ *be functions such that there exists an* $L < 1$ *with* $\varphi(x_1, \cdots, x_n) \leq \frac{L}{v^2}\varphi(vx_1, \cdots, vx_n)$ *for all* $x_1, \cdots, x_n \in X$. *Let* $f : X \to Y$ *be an even mapping satisfying* $f(0) = 0$ *and*

$$N(Pf(x_1, \cdots, x_n), t) \geq \frac{t}{t + \varphi(x_1, \cdots, x_n)} \tag{2.1}$$

for all $x_1, \cdots, x_n \in X$ *and all* $t > 0$. *Then* $Q(x) := N\text{-}\lim_{m\to\infty} v^{2m} f\left(\frac{x}{v^m}\right)$ *exists for each* $x \in X$ *and defines a quadratic mapping* $Q : X \to Y$ *such that*

$$N(f(x) - Q(x), t) \geq \frac{(v^2 - v^2 L)t}{(v^2 - v^2 L)t + L\psi(x)} \tag{2.2}$$

for all $x \in X$ *and all* $t > 0$.

Proof. Letting $x_1 = x_3 = \cdots = x_n = 0$ and $x_2 = x$ in (2.1), we get

$$N\left(f(vx) - v^2 f(x), t\right) \geq \frac{t}{t + \varphi(0, x, \underbrace{0, \cdots, 0}_{n-2 \text{ times}})} = \frac{t}{t + \psi(x)} \tag{2.3}$$

for all $x \in X$.

Consider the set

$$S := \{g : X \to Y\}$$

and introduce the generalized metric on S:

$$d(g, h) = \inf\{\mu \in \mathbb{R}_+ : N(g(x) - h(x), \mu t) \geq \frac{t}{t + \psi(x)}, \ \forall x \in X, \forall t > 0\},$$

where, as usual, $\inf \phi = +\infty$. It is easy to show that (S, d) is complete (see [22, Lemma 2.1]).

Now we consider the linear mapping $J : S \to S$ such that

$$Jg(x) := v^2 g\left(\frac{x}{v}\right)$$

for all $x \in X$.

Let $g, h \in S$ be given such that $d(g, h) = \varepsilon$. Then

$$N(g(x) - h(x), \varepsilon t) \geq \frac{t}{t + \psi(x)}$$

for all $x \in X$ and all $t > 0$. Hence

$$\begin{aligned} N(Jg(x) - Jh(x), L\varepsilon t) &= N\left(v^2 g\left(\frac{x}{v}\right) - v^2 h\left(\frac{x}{v}\right), L\varepsilon t\right) \\ &= N\left(g\left(\frac{x}{v}\right) - h\left(\frac{x}{v}\right), \frac{L}{v^2}\varepsilon t\right) \\ &\geq \frac{\frac{Lt}{v^2}}{\frac{Lt}{v^2} + \psi\left(\frac{x}{v}\right)} \geq \frac{\frac{Lt}{v^2}}{\frac{Lt}{v^2} + \frac{L}{v^2}\psi(x)} \\ &= \frac{t}{t + \psi(x)} \end{aligned}$$

for all $x \in X$ and all $t > 0$. So $d(g, h) = \varepsilon$ implies that $d(Jg, Jh) \leq L\varepsilon$. This means that

$$d(Jg, Jh) \leq Ld(g, h)$$

for all $g, h \in S$.

It follows from (2.3) that

$$N\left(f(x) - v^2 f\left(\frac{x}{v}\right), \frac{Lt}{v^2}\right) \geq \frac{\frac{L}{v^2}t}{\frac{L}{v^2}t + \psi\left(\frac{x}{v}\right)} \geq \frac{t}{t + \psi(x)} \tag{2.4}$$

for all $x \in X$. So $d(f, Jf) \leq \frac{L}{v^2}$.

By Theorem 1.4, there exists a mapping $Q : X \to Y$ satisfying the following:

(1) Q is a fixed point of J, i.e.,

$$Q\left(\frac{x}{v}\right) = \frac{1}{v^2}Q(x) \tag{2.5}$$

for all $x \in X$. Since $f : X \to Y$ is even, $Q : X \to Y$ is an even mapping. The mapping Q is a unique fixed point of J in the set

$$M = \{g \in S : d(f, g) < \infty\}.$$

This implies that Q is a unique mapping satisfying (2.5) such that there exists a $\mu \in (0, \infty)$ satisfying

$$N(f(x) - Q(x), \mu t) \geq \frac{t}{t + \psi(x)}$$

for all $x \in X$;

(2) $d(J^m f, Q) \to 0$ as $m \to \infty$. This implies the equality

$$N\text{-}\lim_{m\to\infty} v^{2m} f\left(\frac{x}{v^m}\right) = Q(x)$$

for all $x \in X$;

(3) $d(f,Q) \le \frac{1}{1-L} d(f,Jf)$, which implies the inequality

$$d(f,Q) \le \frac{L}{v^2 - v^2 L}.$$

This implies that the inequality (2.2) holds.

By (2.1),

$$N\left(v^{2m} Pf\left(\frac{x_1}{v^m}, \cdots, \frac{x_n}{v^m}\right), v^{2m} t\right) \ge \frac{t}{t + \varphi\left(\frac{x_1}{v^m}, \cdots, \frac{x_n}{v^m}\right)}$$

for all $x_1, \cdots, x_n \in X$, all $t > 0$ and all $m \in \mathbb{N}$. So

$$N\left(v^{2m} Pf\left(\frac{x_1}{v^m}, \cdots, \frac{x_n}{v^m}\right), t\right) \ge \frac{\frac{t}{v^{2m}}}{\frac{t}{v^{2m}} + \frac{L^m}{v^{2m}} \varphi\left(x_1, \cdots, x_n\right)}$$

for all $x_1, \cdots, x_n \in X$, all $t > 0$ and all $m \in \mathbb{N}$. Since

$$\lim_{m \to \infty} \frac{\frac{t}{v^{2m}}}{\frac{t}{v^{2m}} + \frac{L^m}{v^{2m}} \varphi\left(x_1, \cdots, x_n\right)} = 1$$

for all $x_1, \cdots, x_n \in X$ and all $t > 0$,

$$N\left(PQ(x_1, \cdots, x_n), t\right) = 1$$

for all $x_1, \cdots, x_n \in X$ and all $t > 0$. Thus the mapping $Q : X \to Y$ is quadratic, as desired. □

COROLLARY 2.2. *Let $\theta \ge 0$ and let p be a real number with $p > 2$. Let X be a normed vector space with norm $\|\cdot\|$. Let $f : X \to Y$ be an even mapping satisfying*

$$N\left(Pf(x_1, \cdots, x_n), t\right) \ge \frac{t}{t + \theta \sum_{j=1}^{n} \|x_j\|^p} \tag{2.6}$$

for all $x_1, \cdots, x_n \in X$ and all $t > 0$. Then $Q(x) := N\text{-}\lim_{m\to\infty} v^{2m} f\left(\frac{x}{v^m}\right)$ exists for each $x \in X$ and defines a quadratic mapping $Q : X \to Y$ such that

$$N\left(f(x) - Q(x), t\right) \ge \frac{(v^p - v^2)t}{(v^p - v^2)t + \theta \|x\|^p}$$

for all $x \in X$ and all $t > 0$.

Proof. The proof follows from Theorem 2.1 by taking

$$\varphi(x_1, \cdots, x_n) := \theta \sum_{j=1}^{n} \|x_j\|^p$$

for all $x_1, \cdots, x_n \in X$. Then we can choose $L = v^{2-p}$ and we get the desired result. □

THEOREM 2.3. *Let* $\varphi : X^n \to [0,\infty)$ *and* $\psi(x) := \varphi(0, x, \underbrace{0, \cdots, 0}_{n-2 \text{ times}})$ *be functions such that there exists an* $L < 1$ *with* $\varphi(x_1, \cdots, x_n) \le v^2 L\varphi\left(\frac{x_1}{v}, \cdots, \frac{x_n}{v}\right)$ *for all* $x_1, \cdots, x_n \in X$. *Let* $f : X \to Y$ *be an odd mapping satisfying* (2.1). *Then* $Q(x) := N\text{-}\lim_{m\to\infty} \frac{1}{v^{2m}} f(v^m x)$ *exists for each* $x \in X$ *and defines a quadratic mapping* $Q : X \to Y$ *such that*

$$N(f(x) - Q(x), t) \ge \frac{(v^2 - v^2L)t}{(v^2 - v^2L)t + \psi(x)} \tag{2.7}$$

for all $x \in X$ *and all* $t > 0$.

Proof. Let (S, d) be the generalized metric space defined in the proof of Theorem 2.1.

Consider the linear mapping $J : S \to S$ such that

$$Jg(x) := \frac{1}{v^2} g(vx)$$

for all $x \in X$.

It follows from (2.3) that

$$N\left(f(x) - \frac{1}{v^2} f(vx), \frac{t}{v^2}\right) \ge \frac{t}{t + \psi(x)}$$

for all $x \in X$ and all $t > 0$. Thus $d(f, Jf) \le \frac{1}{v^2}$.

The rest of the proof is similar to the proof of Theorem 2.1. □

COROLLARY 2.4. *Let* $\theta \ge 0$ *and let* p *be a real number with* $p < 2$. *Let* X *be a normed vector space with norm* $\|\cdot\|$. *Let* $f : X \to Y$ *be an even mapping satisfying* (2.6). *Then* $Q(x) := N\text{-}\lim_{m\to\infty} \frac{1}{v^{2m}} f(v^m x)$ *exists for each* $x \in X$ *and defines a quadratic mapping* $Q : X \to Y$ *such that*

$$N(f(x) - Q(x), t) \ge \frac{(v^2 - v^p)t}{(v^2 - v^p)t + \theta\|x\|^p}$$

for all $x \in X$ *and all* $t > 0$.

Proof. The proof follows from Theorem 2.3 by taking

$$\varphi(x_1, \cdots, x_n) := \theta \sum_{j=1}^{n} \|x_j\|^p$$

for all $x_1, \cdots, x_n \in X$. Then we can choose $L = v^{p-2}$ and we get the desired result. □

3. Hyers-Ulam stability of the quadratic functional equation (1.2) in fuzzy Banach spaces

For a given mapping $f : X \to Y$, we define

$$\begin{aligned} Df(x_1, \cdots, x_n) := f\left(\sum_{i=1}^n d_i x_i\right) + \sum_{1\le i<j\le n} d_i d_j f(x_i - x_j) \\ - \sum_{i=1}^n d_i \left(\sum_{i=1}^n d_i f(x_i)\right) \end{aligned}$$

for all $x_1, \cdots, x_n \in X$.

Using the fixed point method, we prove the Hyers-Ulam stability of the quadratic functional equation $Df(x_1, \cdots, x_n) = 0$ in fuzzy Banach spaces

Theorem 3.1. *Let $\varphi : X^n \to [0, \infty)$ and $\psi(x) := \varphi(\underbrace{x, \cdots, x}_{n\ times})$ be functions such that there exists an $L < 1$ with $\varphi(x_1, \cdots, x_n) \le \frac{L}{d^2}\varphi(dx_1, \cdots, dx_n)$ for all $x_1, \cdots, x_n \in X$. Let $f : X \to Y$ be an even mapping satisfying $f(0) = 0$ and*

$$N(Df(x_1, \cdots, x_n), t) \ge \frac{t}{t + \varphi(x_1, \cdots, x_n)} \tag{3.1}$$

for all $x_1, \cdots, x_n \in X$ and all $t > 0$. Then $Q(x) := N\text{-}\lim_{m\to\infty} d^{2m} f\left(\frac{x}{d^m}\right)$ exists for each $x \in X$ and defines a quadratic mapping $Q : X \to Y$ such that

$$N(f(x) - Q(x), t) \ge \frac{(d^2 - d^2L)t}{(d^2 - d^2L)t + L\psi(x)}$$

for all $x \in X$ and all $t > 0$.

Proof. Letting $x_1 = \cdots = x_l = x$ in (3.1), we get

$$N\left(f(dx) - d^2 f(x), t\right) \ge \frac{t}{t + \varphi(\underbrace{x, \cdots, x}_{n \text{ times}})} = \frac{t}{t + \psi(x)} \tag{3.2}$$

for all $x \in X$.

Consider the set

$$S := \{g : X \to Y\}$$

and introduce the generalized metric on S:

$$d(g, h) = \inf\{\mu \in \mathbb{R}_+ : N(g(x) - h(x), \mu t) \ge \frac{t}{t + \psi(x)},\ \forall x \in X, \forall t > 0\},$$

where, as usual, $\inf \phi = +\infty$. It is easy to show that (S, d) is complete (see [22, Lemma 2.1]).

Now we consider the linear mapping $J : S \to S$ such that

$$Jg(x) := d^2 g\left(\frac{x}{d}\right)$$

for all $x \in X$.

It follows from (3.2) that

$$N\left(f(x) - d^2 f\left(\frac{x}{d}\right), \frac{Lt}{d^2}\right) \ge \frac{\frac{L}{d^2}t}{\frac{L}{d^2}t + \psi\left(\frac{x}{d}\right)} \ge \frac{t}{t + \psi(x)} \tag{3.3}$$

for all $x \in X$. So $d(f, Jf) \le \frac{L}{d^2}$.

The rest of the proof is similar to the proof of Theorem 2.1. □

COROLLARY 3.2. *Let $\theta \ge 0$ and let p be a real number with $p > 2$. Let X be a normed vector space with norm $\|\cdot\|$. Let $f : X \to Y$ be an even mapping satisfying*

$$N(Df(x_1, \cdots, x_n), t) \ge \frac{t}{t + \theta \sum_{j=1}^{n} \|x_j\|^p} \tag{3.4}$$

for all $x_1, \cdots, x_n \in X$ and all $t > 0$. Then $Q(x) := N\text{-}\lim_{m\to\infty} d^{2m} f\left(\frac{x}{d^m}\right)$ exists for each $x \in X$ and defines a quadratic mapping $Q : X \to Y$ such that

$$N(f(x) - Q(x), t) \ge \frac{(d^p - d^2)t}{(d^p - d^2)t + n\theta\|x\|^p}$$

for all $x \in X$ and all $t > 0$.

Proof. The proof follows from Theorem 3.1 by taking

$$\varphi(x_1, \cdots, x_n) := \theta \sum_{j=1}^{n} \|x_j\|^p$$

for all $x_1, \cdots, x_n \in X$. Then we can choose $L = d^{2-p}$ and we get the desired result. □

THEOREM 3.3. *Let $\varphi : X^l \to [0, \infty)$ and $\psi(x) := \varphi(\underbrace{x, \cdots, x}_{n \text{ times}})$ be functions such that there exists an $L < 1$ with $\varphi(x_1, \cdots, x_n) \le d^2 L \varphi(\frac{x_1}{d}, \cdots, \frac{x_n}{d})$ for all $x_1, \cdots, x_n \in X$. Let $f : X \to Y$ be an even mapping satisfying $f(0) = 0$ and (3.1). Then $Q(x) := N\text{-}\lim_{m\to\infty} \frac{1}{d^{2m}} f(d^m x)$ exists for each $x \in X$ and defines a quadratic mapping $Q : X \to Y$ such that*

$$N(f(x) - Q(x), t) \ge \frac{(d^2 - d^2 L)t}{(d^2 - d^2 L)t + \psi(x)}$$

for all $x \in X$ and all $t > 0$.

Proof. Let (S, d) be the generalized metric space defined in the proof of Theorem 3.1.

Consider the linear mapping $J : S \to S$ such that

$$Jg(x) := \frac{1}{d^2} g\,(dx)$$

for all $x \in X$.

It follows from (3.2) that

$$N\left(f(x) - \frac{1}{d^2} f(dx), \frac{t}{d^2}\right) \geq \frac{t}{t + \psi(x)}$$

for all $x \in X$ and all $t > 0$. Thus $d(f, Jf) \leq \frac{1}{d^2}$.

The rest of the proof is similar to the proofs of Theorems 2.1 and 3.1. □

Corollary 3.4. *Let $\theta \geq 0$ and let p be a real number with $p < 2$. Let X be a normed vector space with norm $\|\cdot\|$. Let $f : X \to Y$ be an even mapping satisfying*

$$N\,(Df(x_1, \cdots, x_n), t) \geq \frac{t}{t + \theta \sum_{j=1}^{n} \|x_j\|^p} \tag{3.5}$$

for all $x_1, \cdots, x_n \in X$ and all $t > 0$. Then $Q(x) := N\text{-}\lim_{m\to\infty} d^{2m} f\left(\frac{x}{d^m}\right)$ exists for each $x \in X$ and defines a quadratic mapping $Q : X \to Y$ such that

$$N\,(f(x) - Q(x), t) \geq \frac{(d^2 - d^p)t}{(d^2 - d^p)t + n\theta\|x\|^p}$$

for all $x \in X$ and all $t > 0$.

Proof. The proof follows from Theorem 3.3 by taking

$$\varphi(x_1, \cdots, x_n) := \theta \sum_{j=1}^{n} \|x_j\|^p$$

for all $x_1, \cdots, x_n \in X$. Then we can choose $L = d^{p-2}$ and we get the desired result. □

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