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Kyoto University
Visual Approaches for Numerical Analysis Concerning Fuzzy Differential Equations

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ABSTRACT

By a parametric representation of fuzzy numbers, normal strictly and upper semi-continuous fuzzy numbers with bounded supports are identified with bounded continuous curves in the two-dimensional metric space. We introduce fuzzified oil well equation and discuss the stability of solutions of the fuzzy differential equation (FDE) by the method of parametric representation of fuzzy numbers. We also show that the analysis of fuzzy differential inclusions plays an important role in discussing similar asymptotic behaviors to ordinary differential equations.

Keywords: fuzzy differential equation, fuzzy number, parametric representation, fuzzy differential inclusion.

1. PARAMETRIC REPRESENTATION

Let \( I = [0,1] \). We define the following set of fuzzy numbers, where a fuzzy number \( x \) is characterized by a membership function \( \mu_x \) as follows (cf. [1]):

\[
\begin{align*}
L_\alpha(x) &= \{ \xi \in \mathbb{R} : \mu_x(\xi) \geq \alpha \}.
\end{align*}
\]

In the similar way as [1] we consider the following parametric representation of \( \mu_x \in \mathcal{F}_a^n \) such that
\[
\begin{align*}
x_1(\alpha) &= \min L_\alpha(x_1), \\
x_2(\alpha) &= \max L_\alpha(x_2),
\end{align*}
\]
for \( 0 < \alpha \leq 1 \) and that \( x_1(0) = \min \text{cl} (\text{supp} (\mu_x)), \)
\( x_1(0) = \max \text{cl} (\text{supp} (\mu_x)). \) In what follows we denote a fuzzy numbers by \( x = (x_1, x_2) \).

By applying the above extension principle and the representation of fuzzy numbers we get the following results.

1) Addition. Let \( x = (x_1, x_2), y = (y_1, y_2) \in \mathcal{F}_a^n \).

We get the addition

\[
\begin{align*}
\mu_{x+y}(\xi) &= \sup_{\xi = \xi_1 + \xi_2} \min \{ \mu_x(\xi_1), \mu_y(\xi_2) \} \\
&= \sup \{ \alpha \in I : \xi = \xi_1 + \xi_2, \xi_1 \in x_1, \xi_2 \in y_2 \}
\end{align*}
\]

which means that \( x + y = (x_1 + y_1, x_2 + y_2) \). Here \( x_a = L_\alpha(x_a) \) etc.

2) Subtraction. It follows that

\[
\begin{align*}
\mu_{x-y}(\xi) &= \sup_{\xi = \xi_1 - \xi_2} \min \{ \mu_x(\xi_1), \mu_y(\xi_2) \} \\
&= \sup \{ \alpha \in I : \xi = \xi_1 - \xi_2, \xi_1 \in x_1, \xi_2 \in y_2 \}
\end{align*}
\]

which means that \( x - y = (x_1 - y_1, x_2 - y_2) \).

3) Product. It follows that

\[
\begin{align*}
\mu_{xy}(\xi) &= \sup_{\xi = \xi_1 \xi_2} \min \{ \mu_x(\xi_1), \mu_y(\xi_2) \} \\
&= \sup \{ \alpha \in I : \xi = \xi_1 \xi_2, \xi_1 \in x_1, \xi_2 \in y_2 \}
\end{align*}
\]

which means that the following relation.
By the above parametric representation of fuzzy functions we get the following theorem concerning properties of end-points.

**Theorem 1.** Denote \( x = (x_1, x_2) \in F_{b}^{u} \), where \( x_1, x_2 : I \to R \). Then the following properties (i)-(iii) hold:

(i) \( x_i \in C(I) \), \( i = 1, 2 \). Here \( C(I) \) is the set of all the continuous functions on \( I \);

(ii) There exists a unique \( m \in R \) such that \( x_i(l) = x_i(1) = m \) and \( x_i(\alpha) \leq m \leq x_i(\alpha) \) for \( \alpha \in I \);

(iii) One of the following statements (a) and (b) holds:

(a) Functions \( x_i \) are non-decreasing, non-increasing on \( I \), respectively, with \( x_i(\alpha) \leq m \leq x_i(\alpha) \) for \( 0 < \alpha < 1 \);

(b) \( x_i(\alpha) = x_i(\alpha) \) for \( 0 < \alpha < 1 \).

Conversely, under the above conditions (i)-(iii), if we denote \( \mu_i(\xi) = \sup \{ \alpha \in I : x_i(\alpha) \leq \xi \leq x_i(\alpha) \} \) then \( \mu_i \) is the membership function of \( x_i \), i.e., \( \mu_i \in F_{b}^{u} \). Let a metric between \( x = (x_1, y_1), y = (y_1, y_2) \) be defined as follows:

\[
d(x, y) = \sup_{\alpha \in I} \{ |x_1(\alpha) - y_1(\alpha)| + |x_2(\alpha) - y_2(\alpha)| \}
\]

(1.6)

Then we get following result immediately (see [2,3]).

**Theorem 2.** \( (F_{b}^{u}, d) \) is complete metric space.

2. **CALCULUS OF FUZZY FUNCTIONS**

Consider a function \( x : R \to F_{b}^{u} \). Then \( x(t) \) is said to be a fuzzy function. In [7] we find the following definition of fuzzy functions.

\[
x(t) = (x_1(t, \alpha), x_2(t, \alpha))' \
\]

\( t \in [t_1, t_2] \). Denote \( x(t) = (x_1(t), x_2(t)) \).

A fuzzy function \( x(t) = (x_1(t, \alpha), x_2(t, \alpha)) : R \to F_{b}^{u} \) is H-differentiable at \( t \) in the sense of Hukuhara if there exists an \( R \in F_{b}^{u} \) such that (i) and (ii) hold as \( h \to +0 \).

(i) \( x(t + h) = x(t) + h \eta + o(h) \);

(ii) \( x(t) = x(t - h) + h \eta + o(h) \).

Here \( o(h) = (o_{1}(h), o_{2}(h)) \in C[0, e] \times C[0, e] \) with \( e > 0 \), which means that

\[
\lim_{|h| \to 0} \frac{d(o(h), 0)}{|h|} = 0. \quad (2.2)
\]

Then \( x(t) = (x_1(t), x_2(t)) \) is H-differentiable at \( t \) if and only if \( x_1(t, \alpha), x_2(t, \alpha) \) are differentiable in \( t \) for each \( \alpha \in I \) such that \( \eta = \frac{\partial}{\partial \alpha} \in F_{b}^{u} \).

In [4] the author discuss the integration of fuzzy function \( x(t) \).

**Definition 2.** A fuzzy function \( x(t) = (x_1(t), x_2(t)) \) is called integrable over \( [t_1, t_2] \) if \( x_1(t, \alpha) \) and \( x_2(t, \alpha) \) are integrable over \( [t_1, t_2] \) for \( \alpha \in I \).

Denote \( \int_{t_1}^{t_2} x(s, \alpha) ds = \{ (\int_{t_1}^{t_2} x_1(s, \alpha) ds, \int_{t_1}^{t_2} x_2(s, \alpha) ds)^T \in R^2 : \alpha \in I \} \).

3. **FUZZY DIFFERENTIAL EQUATIONS**

In [5] they discuss exponential decay problems, e.g., machine replacement and oil well extraction, etc. They analyze optimization problems for each oil well to determine its optimal replacement schedule. Denote the quality remaining in the well at time \( t \) by \( x(t) \) and the rate of oil extraction by \( D > 0 \). Then they get the following rate of oil extraction \( x(t) = -Dx \) with \( x(0) = v \). Then \( x(t) = ve^{-Dt} \).

In what follows we consider the rate of oil extraction \( D \) as a constant fuzzy number \( D = (D_1, D_2) \in F_{b}^{u} \), where \( D_1(\alpha) \) is the left end-point of the \( \alpha \)-cut set and \( D_1(\alpha) > 0 \) for \( \alpha \in I \). Then we assume that the oil quality \( x(t) = (x_1(t), x_2(t)) \in F_{b}^{u} \) is a fuzzy function which means the quality remaining in the well at time \( t \) and \( v \in F_{b}^{u} \). Consider an initial value problem of fuzzy differential equation

\[
\frac{d}{dt}(x) = -(Dx), \quad x(0) = v. \quad (3.1)
\]

The above problem has a unique solution

\[
x(t) = v + \int_{0}^{t}(-(Dx(s)))ds. \quad (3.2)
\]

See [6].

It follows that as long as \( x_i(t) \geq 0 \), by the extension of principle
\[
\frac{d}{dt}(x_1(t), x_2(t)) = -(D_1, D_2)(x_1, x_2) \\
= -(D_1 x_2, D_2 x_2) \\
= (-D_2 x_2, -D_1 x_1).
\]

Then we have two ordinary differential equations such as
\[
x_1'(t) = -D x_2, \quad x_2'(t) = -D x_1 \tag{3.4}
\]
with \( x(0) = (v_1, v_2) \in \mathcal{F}_b^{st} \). Therefore
\[
x_1(t) = \frac{v_1 + v_2 \sqrt{D_2}}{2} e^{-\sqrt{D_1} t} + \frac{v_1 - v_2 \sqrt{D_2}}{2} e^{\sqrt{D_1} t},
\]
\[
x_2(t) = \frac{v_1 \sqrt{D_2} + v_2}{2} e^{-\sqrt{D_1} t} - \frac{v_1 \sqrt{D_2} - v_2}{2} e^{\sqrt{D_1} t}, \tag{3.5}
\]
for \( t \geq 0 \). These solutions, \( x_1(t) \) and \( x_2(t) \), decrease with an increase in time, and \( x_1 \) attain zero at the time
\[
t_0 = \frac{1}{2 \sqrt{D_1 D_2}} \ln \left( \frac{\sqrt{D_2} v_2 + v_1}{\sqrt{D_2} v_2 - v_1} \right). \tag{3.7}
\]

After this time \( t_0 \), we must use other system of the differential equations available for \( x_1(t) \leq 0 \). Then it follows that for \( x_1(t) \leq 0 \), by the extension of principle

Then we have two ordinary differential equations such as
\[
x_1'(t) = -D_2 x_2, \quad x_2'(t) = -D_2 x_1 \tag{3.9}
\]

Fig. 1. Triangular membership functions for \( x(0) \) and \( D \) used for the computations.

Fig. 2. Computed results of the fuzzy differential equation (3.1): (a) curves of solutions for each \( \alpha \), (b) temporal evolutions of the bounded continuous curves indicating the membership function.
with $x(t_0) = (0,v_{20}) \in \mathcal{F}_b^e$. Therefore

$$x_1(t-t_0) = \frac{v_{20}}{2}(e^{-D_1(t-t_0)} - e^{D_1(t-t_0)}), \quad \text{and} \quad x_2(t-t_0) = \frac{v_{20}}{2}(e^{-D_2(t-t_0)} + e^{D_2(t-t_0)}).$$

Then we get the unstable result of solution $x = (x_1,x_2)$ such that

$$\lim_{t \to \infty} d(x(t),0) = +\infty$$

where $0 \in R$, as well as it follows that

$$\lim_{t \to \infty} \sup_{\alpha \in I} |D_1(\alpha)x_1(t,\alpha) + D_2(\alpha)x_2(t,\alpha)| = 0$$

(see [3]).

To provide the graphs from these results, we consider membership functions for the initial value $x(0)$ and the constant D as shown in Fig.1. The temporal evolutions calculated are shown in Fig.2. It is found that fuzzy differential equations enlarge its fuzziness of the system as time increases. Although the center of the fuzzy number for the decaying system described shows the exponential decay, other fuzzy numbers show asymptotic behaviors with $x_1(t,\alpha) \to -\infty$ and $x_2(t,\alpha) \to +\infty$ as $t \to +\infty$ for $\alpha \neq 1$.

4 FUZZY DIFFERENTIAL INCLUSIONS

In this section we introduce the idea of fuzzy differential inclusions in [6,7,8,9].

Example. Consider an initial value problem of fuzzy differential equation (3.2). According to the idea of fuzzy differential inclusions in which a family of differential inclusions plays an important role in finding some kind of fuzzy sets of (3.2) (See [10]). Let

$$F(\xi_1,\alpha) = [-D_1(\alpha)\xi_1,-D_1(\alpha)\xi_2] \subset R$$

defined on $R \times J$ to the set of compact and convex sets $K_a^1$ in $R$. Then one can solve the following differential inclusions

$$(\xi_1)'_a(t) \in F(\xi_1,\alpha), \quad \xi_a(0) \in L_a(v) \quad (4.1)$$

where $L_a(v) = [v_1(\alpha),v_2(\alpha)]$ for $\alpha \in I$, which means that differential inequalities

$$-D_1(\alpha)\xi_1(t) \leq (\xi_1)'_a(t) \leq -D_1(\alpha)\xi_2(t)$$

$$v_1(\alpha) \leq \xi_a(0) \leq v_2(\alpha)$$

$$(4.2) \quad (4.3)$$

for $\alpha \in I$. Then we emphasize that the function $\xi_a$ is $R$-valued function defined on $R$ without information on the grade of fuzzy number $x$, so $\xi_a(t)$ is a real numbers but not fuzzy number. By basic calculation we get $\xi_a(0)e^{-D_1(\alpha)t} \leq \xi_a(t) \leq \xi_a(0)e^{-D_1(\alpha)t}$ with $\xi_a(t) \subset L_a(v)$. Therefore we have $\xi_a(t) \subset [v_1e^{-D_1(\alpha)t},v_2e^{-D_1(\alpha)t}]$ for $\alpha \in I$, $t \in R$, which is called a solution set denoted by $S_a(L_a(v),t) = [v_1(\alpha)e^{-D_1(\alpha)t},v_2(\alpha)e^{-D_1(\alpha)t}]$. The solution set $S_a(L_a(v),t)$ is the $\alpha$-cut set of the parametric representation of a fuzzy number $(v_t(e^{-D_1(t)},v_2e^{-D_1(t)})$. Thus we get a fuzzy solution of (3.1) as

$$x(t) = (v_1e^{-D_1(t)},v_2e^{-D_1(t)})$$

for $t \in R$. The temporal evolutions calculated by the fuzzy differential inclusion are shown in Fig.3.
5 CONCLUDING REMARKS

In classical analysis of the initial value problem (3.1) we observe the unstability of solutions by the method of parametric representation of fuzzy numbers. By applying differential inclusions to fuzzy differential equations (FDE) the same results of FDE as those in theory of ordinary differential equations. Much richer properties in fuzzy differential inclusions is significant but, in considering $K^1_{C}$-valued function $F(\xi,\alpha)$, one treats each fuzzy number $x(t) \in y^{st}x(t)$ as a real number $x(t) \in R$. Finally, we get solution sets which are the $\alpha$-cut sets of a fuzzy set. By treating many practical modeling of real systems with uncertainty we can get better conclusions on comparison between fuzzy differential inclusions and the parametric representation of fuzzy numbers.

REFERENCES