Functional differential equations of a type similar to $f'(x) = 2f(2x+1) - 2f(2x-1)$ and its application.

Dynamics of functional equations and numerical simulation.

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Functional differential equations of a type similar to $f'(x) = 2f(2x + 1) - 2f(2x - 1)$ and its application.

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\[ f'(x) = af(\lambda x) + bf(x), \]


By using another method, the author [6] constructed one of the solutions for the equation

\[
\begin{cases}
  f'(x) = af(2x), & x \in \mathbb{R} = (-\infty, +\infty), \\
  f(0) = 0,
\end{cases}
\]

where $a$ is a constant with $a \neq 0$. The solution is not unique. If $f$ is a solution, then a constant times $f$ is also a solution. Our solutions are infinitely differentiable and bounded on $\mathbb{R}$. In [6], the author gave the graph of the solution $f(x)$ of (0.2) with $a = 4$ (Figure 1).

![Graph of $f'(x) = 4f(2x)$](image)

**Figure 1.** $f'(x) = 4f(2x)$
In this paper, we construct a solution for the functional differential equation;

\[(0.3) \quad f^{(n)}(x) = \lambda^{n+1} \sum_{j} c_j \beta_j^n \sum_{l=0}^{n} (-1)^l \binom{n}{l} f(\lambda x - \frac{l-n/2+nk_j}{\beta_j}),\]

where \(\sum_j c_j = 1; \sum_j c_j \beta_j^n < \infty, c_j \geq 0, \inf_j \beta_j > 0, \sup_j |k_j| < \infty\) and \(\sum_j\) is finite sum or infinite sum. The solution is unique in \(L^1(\mathbb{R})\) up to a multiplicative constant and it is in \(C^\infty_{\text{comp}}(\mathbb{R}) \cap L^1(\mathbb{R})\). (Some special cases were treated in [5].) We also give the method of calculating numerical data. For example, the following is a special case of (0.3).

\[(0.4) \quad f'(x) = 4f(2x) - 4f(2x - 1).\]

The graph of the solution of (0.4) is in Figure 2, which is a component of the graph of Figure 1. Our main result is as follows.

![Figure 2. The solution of (0.4).](image)

**Theorem 0.1.** The equation (0.3) has a unique solution in \(L^1(\mathbb{R})\) up to a multiplicative constant and it is in \(C^\infty_{\text{comp}}(\mathbb{R}) \cap L^1(\mathbb{R})\).

We give some examples of (0.3).

(E1) \(f'(x) = 2f(2x + 1) - 2f(2x - 1),\)

(E2) \(f'(x) = 16f(4x) - 16f(4x - 1),\)

(E3) \(f'(x) = (9/4)f(3x/2) - (9/4)f(3x/2 - 1),\)

(E4) \(f'(x) = 3f(2x) - 2f(2x - 1) - f(2x - 2),\)

(E5) \(f'(x) = 3f(2x) - 3f(2x - 1) + f(2x - 2) - f(2x - 3),\)

(E6) \(f'(x) = 4 \sum_{k=0}^{\infty} \sum_{j=1}^{2^k} \frac{1}{2^{k+1}} \sum_{t=-2,-1,1,2} f(2^{k+2}x - \frac{4j + 2t}{2^{k+2}}),\)
(E7) \( f''(x) = 8f(2x + 1) - 16f(2x) + 8f(2x - 1). \)

\[ \begin{align*}
\text{(E1), supp } f &= [0, 1] \\
\text{(E2), supp } f &= [0, 1/3] \\
\text{(E3), supp } f &= [0, 2] \\
\text{(E4), supp } f &= [0, 2] \\
\text{(E5), supp } f &= [0, 3] \\
\end{align*} \]

**Figure 3.** Solution of the equations (E1)–(E5).

\[ \begin{align*}
\text{(E6) and (E7), supp } f &= [0, 2]. \\
\end{align*} \]

**Figure 4.** Solution of the equation (E6) and (E7).

We have considered application of the function (E1) by using "Quark theory" established by H. Trebel. Next section, we introduce the result of application. This application is considered with Yoshihiro Sawano who belongs to Tokyo University.

1. **Result of Application**

**Definition 1.1.** Let \( \rho > 1. \)
Let $0 < p, q \leq \infty$ and $s > \sigma_p$. $B^s_{pq}(\mathbb{R})$ is a set of Schwartz distributions $f$ for which $f$ can be written as

$$
(1.1) \quad f = \sum_{\beta \in \mathbb{N}_0^d} \sum_{\nu=0}^{\infty} \sum_{m \in \mathbb{Z}^d} \lambda_{\nu,m}^{\beta} 2^{-\nu(s-d/p)} (2^\nu x - m)^\beta \phi(2^\nu x - m)
$$

where, the function $\phi$ satisfies $\phi'(x) = 2\phi(2x + 1) - 2\phi(2x - 1)$.

**Theorem 1.1.** The equation

$$
f'(x) = f(x - 1)
$$

can solve explicitly with following initial data

$$
f|_{[0,1]} = \left( \sum_{\beta \in \mathbb{N}_0^d} \sum_{\nu \in \mathbb{N}_0} \sum_{m \in \mathbb{Z}^d : \nu \neq m \in \mathbb{N}_0} \lambda_{\nu,m}^{\beta} 2^{-\nu(s-d/p)} (2^\nu x - m)^\beta \phi(2^\nu x - m) \right) \bigg|_{x \in [0,1]}.
$$

The solution $f|_{[1,2]}$ can be written as follows;

$$
f(x) = f(1) + \sum_{\beta \in \mathbb{N}_0^d} \sum_{\nu \in \mathbb{N}_0} \sum_{m \in \mathbb{Z}^d : \nu \neq m \in \mathbb{N}_0} 2^{-\nu} \lambda_{\nu,m}^{\beta} \phi_{\nu,m}^\beta(x - 1)
$$

$$
+ \left( \int_{\mathbb{R}} x^\beta \phi(x) \, dx \right) \sum_{\nu \in \mathbb{N}_0} \sum_{2 \leq 2^{\nu}} \left( \sum_{l=0}^{m-2} \lambda_{\nu,l}^0 2^{-\nu} \phi(2^\nu x - m - 1) \right).
$$

where

$$
\phi_{\nu,m}^\beta(x) := \left( \sum_{\gamma=0}^{\beta} (-1)^{\gamma} \binom{\beta}{\gamma} (2^\nu x - m)^{\beta-\gamma} I_\gamma(\phi(2^\nu x - m)) \right)
$$

$$
- 2^{-\nu(s-d/p)} \int_{\mathbb{R}} x^\beta \phi(x) \, dx \sum_{l=2}^{\infty} \phi(x - l) - m,
$$

$$
I_\beta(\phi)(x) = \sum_{j_{\beta+1}=0}^{\infty} \sum_{j_{\beta}=0}^{\infty} \ldots \sum_{j_1=0}^{\infty} 2^{\beta(\beta+1)/2} \phi \left( \frac{x - 2^{\beta+1} + 1}{2^{\beta+1}} - \sum_{\gamma=1}^{\beta+1} \frac{j_\gamma}{2^{\gamma-1}} \right)
$$

and

$$
I_0(\phi)(x) = \sum_{j=0}^{\infty} \phi \left( \frac{x - 1 - 2j}{2} \right).
$$

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