

Exponential Stability of Impulsive Stochastic Delay Partial Differential Equations with Poisson Jumps

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Abstract: Up to now, the stability problem of mild solution for the impulsive stochastic system with Poisson jumps has not been solved. In this paper, based on fixed point theory, the stability of mild solutions for impulsive stochastic delay partial differential equations with Poisson jumps is studied, and a number of sufficient conditions are obtained to ensure the expected results. In particular, by taking the Poisson jumps into consideration, the conclusion derived from this work generalizes the results obtained using Luo's publication.

Key words: impulsive stochastic differential equation; exponential stability; mild solution; Poisson jumps

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It is well known, stochastic partial differential equations can be widely used to study many problems in science and engineering. And the qualitative properties of solutions of stochastic partial differential equations have been considered by many authors. As we know, it is impossible to analyze the stability of mild solutions to stochastic differential equations with delays by Lyapunov's method since Itô formula is not suitable for mild solutions. Thus, it is necessary to find good ways to solve this problem. Recently, Lin^[1] investigated the stability of mild solutions of stochastic delay differential equations by using the approximating system and the limiting argument. Based on the technique of stochastic integral and Gronwall inequality, Caraballo et al^[2] studied the exponential stability of mild solutions to stochastic partial differential equations with delays. Later, Luo^[3] also solved the same problem by using fixed point theory.

In recent years, Poisson jumps have been gained much attentions since Poisson jumps not only exist widely but also can be used to study many phenomena in the real lives. Therefore, it is necessary to consider the Poisson jumps into the stochastic system. On the other hand, except stochastic and delay as well as Poisson jumps' effects, impulsive effects is likely to exist widely in variety of evolution processes in which states are changed abruptly at some moments of time, including such fields as finance, medicine, electronics and mechanic, etc. Therefore, it is natural to consider the effect of impulsive when studying the stability of stochastic partial differential equations. For instance, Luo and Liu^[4] studied the exponential stability of mild solutions to stochastic evolution equations with Poisson jumps and Markovian switching, meanwhile, based on comparison principles, some stability criteria were obtained. Furthermore, by estimating the coefficients

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functions in the stochastic energy equality, in Hou et al^[5], the exponential stability of energy solutions for stochastic partial differential equations with variable delays and jumps is discussed, besides, Hou et al^[5] studied almost surely exponential stability of energy solutions for the system considered by Borel-Cantelli lemma and Chebyshev inequality.

Motivated by the above discussion, in this paper we study the stability problem for a class of impulsive stochastic partial differential equations with delays and Poisson jumps. The main aim is to close this gap between impulsive stochastic partial differential equations with delays and Poisson jumps. We prove that the mild solution to a class of impulsive stochastic partial differential equations with delays and Poisson jumps is not only existent and unique but also p th moment exponentially stable by using fixed point theory.

1 Preliminaries

Throughout this work, we use the following notations. Let $\{\Omega, F, P\}$ be a complete probability space with a filtration $\{F_t\}_{t \geq 0}$ satisfying the usual conditions. Then, let H, K be two real separable Hilbert spaces and we denote their inner products by $\|\cdot\|_H, \|\cdot\|_K$ respectively. $L(K, H)$ denotes the set of all bounded linear operators from K into H , and we denote the notation $\|\cdot\|$ for the norm of $L(K, H)$. In this paper, we always use the same symbol $\|\cdot\|$ to denote norms of operators regardless of the spaces potentially involved when no confusion possibly arises. Let $W(t)$ be a Wiener process defined on $\{\Omega, F, P\}$ and take values in the separable Hilbert space K , with covariance operator Q ^[6]. Furthermore, Let $\tau > 0$ and $D := D([- \tau, 0]; H)$ denotes the family of all right-continuous functions with left-hand limits φ from $[- \tau, 0]$ to H , and D is supposed to be equipped with the norm $\|\varphi\|_D = \sup_{-\tau \leq \theta \leq 0} \|\varphi(\theta)\|_H$. Using $D_{F_0}^b([- \tau, 0]; H)$ to denote the family of all almost surely bounded, F_0 -measurable, $D([- \tau, 0]; H)$ -valued

random variables. A is the infinitesimal generator of some C_0 -semigroup of bounded linear operators $T(t)$, $t \geq 0$ on H , and $D(A) \subset H$.

Let $\tilde{N}(dt, du) := N(dt, du) - dt\nu(du)$ is a Poisson random measure with parameter $dt\nu(du)$, where $t \in R_+$, $u \in K$.

In this work, we consider the following semilinear impulsive stochastic partial differential delay equations driven by Poisson jumps

$$\begin{aligned} dx(t) = & [Ax(t) + f(t, x(t - \rho(t)))]dt + \\ & g(t, x(t - \delta(t)))dW(t) + \int_K h(t, x(t - \beta(t)), u) \cdot \\ & \tilde{N}(dt, du), t \geq 0, t \neq t_k, \end{aligned} \quad (1)$$

$$\begin{aligned} \Delta x(t_k) = & x(t_k^+) - x(t_k^-) = I_k(x(t_k^-)), \quad t = t_k, \\ & k = 1, 2, \dots, m, \end{aligned} \quad (2)$$

$$x_0(\cdot) = \xi \in D_{F_0}^b([- \tau, 0]; H), \quad (3)$$

where the mappings

$$\begin{aligned} f : & R_+ \times D([- \tau, 0]; H) \rightarrow H, \\ g : & R_+ \times D([- \tau, 0]; H) \rightarrow L(K, H), \\ h : & R_+ \times D([- \tau, 0]; H) \times K \rightarrow H, \end{aligned}$$

are all Borel measurable; $\rho, \delta, \beta : R_+ \rightarrow [0, \tau]$ are continuous; $I_k : H \rightarrow H$. Moreover, $x(t_k^+)$ and $x(t_k^-)$ denote the right-hand and left-hand limits of $x(t)$ at time $t = t_k$ respectively, and the fixed moments t_k satisfy $0 < t_1 < \dots < t_m < \lim_{k \rightarrow \infty} t_k = \infty$; $\Delta x(t_k) = x(t_k^+) - x(t_k^-)$ denote the jumps in the state at time t_k with I_k which determine the size of the jumps, $k = 1, 2, \dots, m$.

Now, we introduce the definition of mild solution for stochastic system (1)–(3) and recall the definitions of p th moment exponential stability and almost surely p th moment exponential stability.

Definition 1 A stochastic process $\{x(t), t \in [0, T]\}$, $0 \leq T < +\infty$, is called mild solution of Eq. (1)–(3) if

- (i) $x(t)$ is adapted to $F_t, t \geq 0$;
- (ii) $x(t) \in H$ is continuous on $t \in [0, T]$ almost surely, and for each $0 \leq t \leq T$,

$$\begin{aligned} x(t) = & T(t)\xi(0) + \int_0^t T(t-s)f(s, x(s - \rho(s)))ds + \\ & \int_0^t T(t-s)g(s, x(s - \delta(s)))dW(s) + \\ & \int_0^t \int_K T(t-s)h(s, x(s - \beta(s)), u)\tilde{N}(ds, du) + \\ & \sum_{0 \leq t_k < t} T(t-t_k)I_k(x(t_k^-)), \end{aligned} \quad (4)$$

and $x_0(\cdot) = \xi \in D_{F_0}^b([-\tau, 0]; H)$.

Definition 2 Let $p \geq 2$. Eq. (4) is said to be exponentially stable in the p th moment, if for any initial value ξ , there exist a pair of positive constants $\lambda > 0$ and $L > 0$ such that

$$E \|x(t)\|_H^p \leq L \|\xi\|_D^p e^{-\lambda t}, t \geq 0. \quad (5)$$

Definition 3 Let $p \geq 2$. Eq. (4) is said to be almost surely exponentially stable in the p th moment if there exist $\lambda > 0$ and $T(\omega) > 0$ such that

$$\|x(t)\|_H^p \leq e^{\lambda/2} e^{-\lambda t/2}, \text{ a.s. for } t > T(\omega). \quad (6)$$

Moreover, in order to study the stability of the system (4), we impose the following assumptions:

$$(H1) \quad \|T(t)\|_H \leq Q e^{-at}, \forall t \geq 0,$$

where $Q \geq 1$ and $a > 0$;

$$(H2) \quad \|f(t, x) - f(t, y)\|_H < L_1 \|x - y\|_H, \forall t \geq 0, \\ x, y \in H, \text{ where } L_1 > 0;$$

$$(H3) \quad \|g(t, x) - g(t, y)\|_H < L_2 \|x - y\|_H, \\ \forall t \geq 0, x, y \in H, \text{ where } L_2 > 0;$$

$$(H4) \quad \int_K \|h(t, x) - h(t, y)\|_H v(du) < L_3 \|x - y\|_H, \\ \forall t \geq 0, x, y \in H, \text{ where } L_3 > 0;$$

$$(H5) \quad E \int_0^t \int_K \|h(s, x(s - \beta(s)), u)\|_H v(du) ds < \infty, \\ \forall t \geq 0;$$

$$(H6) \quad E \int_0^t \int_K \|h(s, x(s - \beta(s)), u)\|_H^2 v(du) ds < \infty, \\ \forall t \geq 0;$$

$$(H7) \quad \|I_k(x) - I_k(y)\|_H \leq q_k \|x - y\|_H, \\ \forall x, y \in H, \text{ where } q_k > 0, k = 1, 2, \dots, m.$$

2 Exponential stability of impulsive stochastic system

In this section, we will apply fixed point theory to study the p th moment exponential stability of mild solution for the system (1)–(3). To this end, we shall assume that for any

$$t \geq 0, u \in K, f(t, 0) \equiv 0, g(t, 0) \equiv 0, h(t, 0, u) \equiv 0,$$

and $I_k(0) \equiv 0$ ($k = 1, 2, \dots, m$).

When $\xi \equiv 0$, it is easy to see that Eq. (1)–(3) has a trivial solution.

Let B be the Banach space of all F_t -adapted

processes $\varphi(t, \omega) : [-\tau, \infty) \times \Omega \rightarrow R$. Besides, for any fixed $\omega \in \Omega$, $\varphi(t, \omega)$ is almost surely continuous in t and $\varphi(s, \omega) = \xi(s)$ for $s \in [-\tau, 0]$. Moreover, there exists some b ($0 < b < a$), such that $e^{bt} E \|\varphi(t, \omega)\|_H^p \rightarrow 0$ as $t \rightarrow \infty$ and $e^{bt} / (a - b) < 1/a$.

Theorem 1 Let $p \geq 2$ and suppose that (H1)–(H7) hold, then Eq. (4) is exponentially stable in the p th moment if

$$5^{p-1} Q^p (L_1^p a^{-p} + L_2^p C_p M_p (1/a) + \\ L_3^{p/2} C_p M_p (1/a) + m^{p-1} \sum_{k=1}^m q_k^p) < 1, \quad (7)$$

hold, where $C_p = (p^{p+1} / 2(p-1)^{p-1})^{p/2}$, $M_p = (2a(p-1) / (p-2))^{1-p/2}$.

Proof We define an operator $\Psi : B \rightarrow B$ by $(\Psi x)(t) = \varphi(t)$, for $t \in [-\tau, 0]$, and for $t \geq 0$,

$$(\Psi x)(t) = T(t)\xi(0) + \int_0^t T(t-s)f(s, x(s-\rho(s)))ds + \\ \int_0^t T(t-s)g(s, x(s-\delta(s)))dW(s) + \\ \int_0^t \int_K T(t-s)h(s, x(s-\beta(s)), u)\tilde{N}(ds, du) + \\ \sum_{0 \leq t_k < t} T(t-t_k)I_k(x(t_k^-)) = \\ F_1(t) + F_2(t) + F_3(t) + F_4(t) + F_5(t). \quad (8)$$

In what follows, we will divide the proof into three steps.

Firstly, we prove that Ψ is continuous in the p th moment on $[0, \infty)$. Let $x \in B$, $t_0 \geq 0$ and $|r|$ be sufficiently small, then

$$E \|(\Psi x)(t_0 + r) - (\Psi x)(t_0)\|_H^p \leq \\ 5^{p-1} \sum_{i=1}^5 E \|F_i(t_0 + r) - F_i(t_0)\|_H^p.$$

It is easy to derive that

$$\lim_{r \rightarrow 0} E \|F_i(t_0 + r) - F_i(t_0)\|_H^p = 0, i = 1, 2, 5. \quad (9)$$

Moreover, we obtain

$$E \|F_3(t_0 + r) - F_3(t_0)\|_H^p \leq \\ 2^{p-1} E \left\| \int_0^{t_0} (T(t_0 + r - s) - T(t_0 - s)) \cdot \right. \\ \left. g(s, x(s - \delta(s)))dW(s) \right\|_H^p + \\ 2^{p-1} E \left\| \int_{t_0}^{t_0+r} T(t_0 + r - s) \cdot \right. \\ \left. g(s, x(s - \delta(s)))dW(s) \right\|_H^p, \quad (10) \\ E \|F_4(t_0 + r) - F_4(t_0)\|_H^p \leq \\ 2^{p-1} E \left\| \int_0^{t_0} \int_K (T(t_0 + r - s) - T(t_0 - s)) \cdot \right.$$

$$\begin{aligned} & h(s, x(s - \beta(s)), u) \tilde{N}(ds, du) \|_H^p + \\ & 2^{p-1} E \left\| \int_{t_0}^{t_0+r} \int_K T(t_0 + r - s) \cdot \right. \\ & \left. h(s, x(s - \beta(s)), u) \tilde{N}(ds, du) \|_H^p. \end{aligned} \quad (11)$$

Hence, from (10) and (11), it is easy to know

$$\lim_{r \rightarrow 0} E \| F_j(t_0 + r) - F_j(t_0) \|_H^p = 0, j = 3, 4, \quad (12)$$

which together with (9) yields that Ψ is p th moment continuous.

Next, we show that $\Psi(B) \subset B$. Using (8), we have

$$\begin{aligned} & e^{bt} E \| (\Psi x)(t) \|_H^p \leq \\ & 5^{p-1} e^{bt} E \| T(t) \xi(0) \|_H^p + 5^{p-1} e^{bt} \cdot \\ & E \left\| \int_0^t T(t-s) f(s, x(s - \rho(s))) ds \right\|_H^p + \\ & 5^{p-1} e^{bt} E \left\| \int_0^t T(t-s) g(s, x(s - \delta(s))) dW(s) \right\|_H^p + \\ & 5^{p-1} e^{bt} E \left\| \int_0^t \int_K T(t-s) h(s, x(s - \beta(s)), u) \cdot \right. \\ & \left. \tilde{N}(ds, du) \|_H^p + 5^{p-1} e^{bt} E \left\| \sum_{0 \leq t_k < t} T(t - t_k) \cdot \right. \right. \\ & \left. \left. I_k(x(t_k^-)) \right\|_H^p := J_1(t) + J_2(t) + J_3(t) + \right. \\ & \left. J_4(t) + J_5(t). \end{aligned} \quad (13)$$

Obviously, using assumption (H1), we have

$$\begin{aligned} & J_1(t) \leq 5^{p-1} Q^p e^{-(ap-b)t} \| \xi(0) \|_H^p \leq \\ & 5^{p-1} Q^p e^{-(ap-b)t} \| \xi \|_D^p \rightarrow 0, \text{ as } t \rightarrow \infty. \end{aligned} \quad (14)$$

From assumptions (H1) and (H2) as well as Hölder's inequality, we obtain

$$\begin{aligned} & J_2(t) \leq 5^{p-1} Q^p L_1^p e^{bt} E \left[\int_0^t e^{-a(t-s)} \| x(s - \rho(s)) \|_H ds \right]^p \leq \\ & 5^{p-1} Q^p L_1^p a^{1-p} e^{bt} \int_0^t e^{-a(t-s)} E \| x(s - \rho(s)) \|_H^p ds \leq \\ & 5^{p-1} Q^p L_1^p a^{1-p} e^{bt} e^{-(a-b)t} \int_0^t e^{(a-b)s} e^{b(s-\rho(s))} \cdot \\ & E \| x(s - \rho(s)) \|_H^p ds. \end{aligned} \quad (15)$$

Then for every $x(t) \in B$ and every $\varepsilon > 0$, there exists some $t_1 > 0$ such that

$$e^{b(t-\rho(t))} E \| x(t - \rho(t)) \|_H^p < \varepsilon,$$

for $t \geq t_1$. So (15) yields

$$\begin{aligned} & J_2(t) \leq 5^{p-1} Q^p L_1^p a^{1-p} e^{bt} e^{-(a-b)t} \int_0^{t_1} e^{(a-b)s} e^{b(s-\rho(s))} \cdot \\ & E \| x(s - \rho(s)) \|_H^p ds + 5^{p-1} Q^p L_1^p a^{1-p} e^{bt} e^{-(a-b)t} \cdot \\ & \int_{t_1}^t e^{(a-b)s} e^{b(s-\rho(s))} E \| x(s - \rho(s)) \|_H^p ds \leq \\ & 5^{p-1} Q^p L_1^p a^{1-p} e^{bt} e^{-(a-b)t} \int_0^{t_1} e^{(a-b)s} e^{b(s-\rho(s))} \cdot \\ & E \| x(s - \rho(s)) \|_H^p ds + 5^{p-1} Q^p L_1^p a^{-p} \varepsilon. \end{aligned} \quad (16)$$

Based on (7) and $\lim_{t \rightarrow \infty} e^{-(a-b)t} = 0$, it is easy to see

that there exists some $t_2 \geq t_1$ such that for any $t \geq t_2$ the following holds

$$\begin{aligned} & 5^{p-1} Q^p L_1^p a^{1-p} e^{bt} e^{-(a-b)t} \int_0^{t_1} e^{(a-b)s} e^{b(s-\rho(s))} \cdot \\ & E \| x(s - \rho(s)) \|_H^p ds \leq \varepsilon - 5^{p-1} Q^p L_1^p a^{-p} \varepsilon. \end{aligned} \quad (17)$$

By the above and (16), we obtain

$$\begin{aligned} & \lim_{t \rightarrow \infty} J_2(t) = \lim_{t \rightarrow \infty} 5^{p-1} e^{bt} E \left\| \int_0^t T(t-s) \cdot \right. \\ & \left. f(s, x(s - \rho(s))) ds \right\|_H^p = 0. \end{aligned} \quad (18)$$

Further, for every $x(t) \in B$, $t \in [0, \infty)$ and $p > 2$, we obtain

$$\begin{aligned} & J_3(t) \leq 5^{p-1} Q^p L_2^p C_p e^{bt} \left[\int_0^t e^{-2a((p-1)/(p-2))(t-s)} ds \right]^{(p-2)/2} \cdot \\ & \int_0^t e^{-a(t-s)} E \| x(s - \delta(s)) \|_H^p ds \leq \\ & 5^{p-1} Q^p L_2^p C_p M_p e^{bt} e^{-(a-b)t} \int_0^t e^{(a-b)s} e^{b(s-\delta(s))} \cdot \\ & E \| x(s - \delta(s)) \|_H^p ds, \end{aligned} \quad (19)$$

$$\begin{aligned} & J_4(t) \leq 5^{p-1} Q^p L_3^{p/2} C_p M_p e^{bt} \int_0^t e^{-a(t-s)} \cdot \\ & E \| x(s - \beta(s)) \|_H^p ds \leq 5^{p-1} Q^p L_3^{p/2} C_p \cdot \\ & M_p e^{bt} e^{-(a-b)t} \int_0^t e^{(a-b)s} e^{b(s-\beta(s))} \cdot \\ & E \| x(s - \beta(s)) \|_H^p ds. \end{aligned} \quad (20)$$

It is easy to see when $p = 2$, inequality (21) and (22) also hold with $0^0 := 1$. Thus, for any $p \geq 2$, we obtain

$$\begin{aligned} & J_3(t) \leq 5^{p-1} Q^p L_2^p C_p M_p e^{bt} e^{-(a-b)t} \cdot \\ & \int_0^t e^{(a-b)s} e^{b(s-\delta(s))} E \| x(s - \delta(s)) \|_H^p ds, \end{aligned} \quad (21)$$

$$\begin{aligned} & J_4(t) \leq 5^{p-1} Q^p L_3^{p/2} C_p M_p e^{bt} e^{-(a-b)t} \cdot \\ & \int_0^t e^{(a-b)s} e^{b(s-\beta(s))} E \| x(s - \beta(s)) \|_H^p ds. \end{aligned} \quad (22)$$

As in the proof of (18), it follows from (21) and (22) that

$$\begin{aligned} & \lim_{t \rightarrow \infty} J_3(t) = \lim_{t \rightarrow \infty} 5^{p-1} e^{bt} E \left\| \int_0^t T(t-s) \cdot \right. \\ & \left. g(s, x(s - \delta(s))) dW(s) \right\|_H^p = 0, \end{aligned} \quad (23)$$

$$\begin{aligned} & \lim_{t \rightarrow \infty} J_4(t) = \lim_{t \rightarrow \infty} 5^{p-1} e^{bt} E \left\| \int_0^t \int_K T(t-s) \cdot \right. \\ & \left. h(s, x(s - \beta(s)), u) \tilde{N}(ds, du) \right\|_H^p = 0. \end{aligned} \quad (24)$$

By assumptions (H1) and (H7), we can easily obtain that

$$J_5(t) \leq 5^{p-1} m^{p-1} Q^p e^{bt} \sum_{k=1}^m e^{-ap(t-t_k)} q_k^p E \| x(t_k^-) \|_H^p, \quad (25)$$

thus, the following holds

$$\lim_{t \rightarrow \infty} J_5(t) = \lim_{t \rightarrow \infty} 5^{p-1} e^{bt} \cdot$$

$$E \left\| \sum_{0 < t_k < t} T(t-t_k) I_k(x(t_k^-)) \right\|_H^p = 0. \quad (26)$$

Obviously, from (13), (14), (18), (23), (24) and (26), we know that $e^{bt} E \left\| (\Psi x)(t) \right\|_H^p \rightarrow 0$ as $t \rightarrow \infty$, so we can conclude that $\Psi(B) \subset B$.

Finally, we verify that Ψ is contractive. Similar to the above discussion, for any $x, y \in B$ and fixed $T \in (0, \infty)$, we obtain

$$E \sup_{t \in [0, T]} \left\| (\Psi x)(t) - (\Psi y)(t) \right\|_H^p \leq O_p \times E \sup_{t \in [0, T]} \left\| x(t) - y(t) \right\|_H^p, \quad (27)$$

where

$$O_p = 4^{p-1} Q^p (L_1^p a^{1-p} + L_2^p C_p M_p (1/a) + L_3^{p/2} C_p M_p (1/a) + m^{p-1} \sum_{k=1}^m q_k^p),$$

by using this fact and (7), we verify that Ψ is a contraction mapping. Based on contraction mapping principle, we obtain that Ψ has a unique fixed point $x(t)$ in B which is a solution of Eq. (4). Moreover, $x(s) = \xi(s)$, $s \in [-\tau, 0]$ and $e^{bt} E \left\| x(t) \right\|_H^p \rightarrow 0$ as $t \rightarrow \infty$. Thus, by Definition 2, we know that Eq. (4) is

p th moment exponential stability. The proof is completed.

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带泊松跳的随机脉冲时滞偏微分方程的指数稳定性

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摘要: 带泊松跳的随机脉冲系统的适定性解的稳定性问题至今尚未得到解决. 基于不动点理论, 研究了随机脉冲时滞偏微分方程的适定性解的稳定性, 得到了一些确保所证结论的充分条件. 由于考虑了脉冲和泊松跳, 文中的结论推广了 Luo 所得到的结论.

关键词: 随机脉冲微分方程; 指数稳定性; 适定性解; 泊松跳

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