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Interval oscillation criteria for forced mixed nonlinear impulsive differential equations with variable delay

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Abstract: In this paper, the interval qualitative properties of a class of mixed nonlinear impulsive differential equations are studied. Under the hypothesis of delay $\sigma(t)$ being variable, the ratio of functions $x(t-\sigma(t))$ and $x(t)$ on each considered interval is estimated, then Riccati transformation and ω functions are applied to obtain interval oscillation criteria. The results gained by Özbekler and Zafer [*Comput. Math. Appl.*, 2011] for delay $\sigma(t)=0$ and by Guo *et al.* [*Abstr. Appl. Anal.*, 2012] for delay $\sigma(t)$ being nonnegative constant are developed.

Keywords: Interval oscillation; Impulsive differential equation; Variable delay; Interval delay function

AMS subject classification: 34C15, 34A37, 34K45

1 Introduction

In this paper, we consider the following mixed nonlinear impulsive differential equations with variable delay

$$\begin{aligned} &\big(r(t)\Phi_\alpha(x'(t))\big)' + p_0(t)\Phi_\alpha(x(t)) + \sum_{i=1}^{n} p_i(t)\Phi_{\beta_i}(x(t-\sigma(t))) = f(t),\ t\geq t_0,\ t\neq\tau_k, \\ &x(\tau_k^+) = a_k x(\tau_k), \quad x'(\tau_k^+) = b_k x'(\tau_k), \quad k=1,2,\ldots, \end{aligned} \tag{1.1}$$

where $\Phi_*(s)=|s|^{*-1}s$, $\{\tau_k\}$ denotes the impulse moments sequence, $0\leq t_0=\tau_0<\tau_1<\tau_2<\cdots<\tau_k<\cdots$ and $\lim_{k\to\infty}\tau_k=\infty$.

In 2011, when $\sigma(t)=0$, Özbekler and Zafer [1] and Guo *et al.* [2] investigated (1.1) and established some interval oscillation results. In 2012, when $\sigma(t)$ is a nonnegative constant σ, by idea of [3], Guo *et al.* [4] studied (1.1). They corrected some errors in proof of [3] (cf. Remark 2.4 in [4]) and obtained some results which developed some known results of [1, 2, 5].

However, for the impulsive equations, almost all of interval oscillation results in the existing literature were established only for the case of "without delay" (e.g. [6–8]) or "with constant delay" (e.g. [3, 4, 9]). In other words, for the case of "with variable delay" the study on the interval oscillation of impulsive differential equations is very scarce. To the best of our knowledge, Zhou and Wang [10] gave the first research in this direction in 2016. They considered the following equations

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