

## Research Article

# Oscillation Criteria for Certain Second-Order Nonlinear Neutral Differential Equations of Mixed Type

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Received 19 September 2010; Accepted 19 January 2011

Academic Editor: Josef Diblík

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Some oscillation criteria are established for the second-order nonlinear neutral differential equations of mixed type  $[(x(t) + p_1x(t - \tau_1) + p_2x(t + \tau_2))^\gamma]'' = q_1(t)x^\gamma(t - \sigma_1) + q_2(t)x^\gamma(t + \sigma_2)$ ,  $t \geq t_0$ , where  $\gamma \geq 1$  is a quotient of odd positive integers. Our results generalize the results given in the literature.

## 1. Introduction

This paper is concerned with the oscillatory behavior of the second-order nonlinear neutral differential equation of mixed type

$$[(x(t) + p_1x(t - \tau_1) + p_2x(t + \tau_2))^\gamma]'' = q_1(t)x^\gamma(t - \sigma_1) + q_2(t)x^\gamma(t + \sigma_2), \quad t \geq t_0. \quad (1.1)$$

Throughout this paper, we will assume the following conditions hold.

(A<sub>1</sub>)  $p_i$ ,  $\tau_i$ , and  $\sigma_i$ ,  $i = 1, 2$ , are positive constants;

(A<sub>2</sub>)  $q_i \in C([t_0, \infty), [0, \infty))$ ,  $i = 1, 2$ .

By a solution of (1.1), we mean a function  $x \in C([T_x, \infty), \mathbb{R})$  for some  $T_x \geq t_0$  which has the property that  $(x(t) + p_1x(t - \tau_1) + p_2x(t + \tau_2))^\gamma \in C^2([T_x, \infty), \mathbb{R})$  and satisfies (1.1) on  $[T_x, \infty)$ . As is customary, a solution of (1.1) is called oscillatory if it has arbitrarily large zeros on  $[t_0, \infty)$ , otherwise, it is called nonoscillatory. Equation (1.1) is said to be oscillatory if all its solutions are oscillatory.

Neutral functional differential equations have numerous applications in electric networks. For instance, they are frequently used for the study of distributed networks containing lossless transmission lines which rise in high speed computers where the lossless transmission lines are used to interconnect switching circuits; see [1].

Recently, many results have been obtained on oscillation of nonneutral continuous and discrete equations and neutral functional differential equations, we refer the reader to the papers [2–35], and the references cited therein.

Philos [2] established some Philos-type oscillation criteria for the second-order linear differential equation

$$(r(t)x'(t))' + q(t)x(t) = 0, \quad t \geq t_0. \quad (1.2)$$

In [3–5], the authors gave some sufficient conditions for oscillation of all solutions of second-order half-linear differential equation

$$\left(r(t)|x'(t)|^{r-1}x'(t)\right)' + q(t)|x(\tau(t))|^{r-1}x(\tau(t)) = 0, \quad t \geq t_0 \quad (1.3)$$

by employing a Riccati substitution technique.

Zhang et al. [15] examined the oscillation of even-order neutral differential equation

$$[x(t) + p(t)x(\tau(t))]^{(n)} + q(t)f(x(\sigma(t))) = 0, \quad t \geq t_0. \quad (1.4)$$

Some oscillation criteria for the following second-order quasilinear neutral differential equation

$$\left(r(t)|z'(t)|^{r-1}z'(t)\right)' + q(t)|x(\sigma(t))|^{r-1}x(\sigma(t)) = 0, \quad \text{for } z(t) = x(t) + p(t)x(\tau(t)), \quad t \geq t_0 \quad (1.5)$$

were obtained by [12–17].

However, there are few results regarding the oscillatory properties of neutral differential equations with mixed arguments, see the papers [20–24]. In [25], the authors established some oscillation criteria for the following mixed neutral equation:

$$(x(t) + p_1x(t - \tau_1) + p_2x(t + \tau_2))'' = q_1(t)x(t - \sigma_1) + q_2(t)x(t + \sigma_2), \quad t \geq t_0; \quad (1.6)$$

here  $q_1$  and  $q_2$  are nonnegative real-valued functions. Grace [26] obtained some oscillation theorems for the odd order neutral differential equation

$$(x(t) + p_1x(t - \tau_1) + p_2x(t + \tau_2))^{(n)} = q_1x(t - \sigma_1) + q_2x(t + \sigma_2), \quad t \geq t_0, \quad (1.7)$$

where  $n \geq 1$  is odd. Grace [27] and Yan [28] obtained several sufficient conditions for the oscillation of solutions of higher-order neutral functional differential equation of the form

$$(x(t) + cx(t - h) + Cx(t + H))^{(n)} + qx(t - g) + Qx(t + G) = 0, \quad t \geq t_0, \quad (1.8)$$

where  $q$  and  $Q$  are nonnegative real constants.

Clearly, (1.6) is a special case of (1.1). The purpose of this paper is to study the oscillation behavior of (1.1).

In the sequel, when we write a functional inequality without specifying its domain of validity we assume that it holds for all sufficiently large  $t$ .

## 2. Main Results

In the following, we give our results.

**Theorem 2.1.** *Assume that  $\sigma_i > \tau_i$ ,  $i = 1, 2$ . If*

$$\limsup_{t \rightarrow \infty} \int_t^{t+\sigma_2-\tau_2} (t + \sigma_2 - \tau_2 - s)Q_2(s)ds > (2^{\gamma-1})^2 \left( 1 + p_1^\gamma + \frac{p_2^\gamma}{2^{\gamma-1}} \right), \quad (2.1)$$

$$\limsup_{t \rightarrow \infty} \int_{t-\sigma_1+\tau_1}^t (s - t + \sigma_1 - \tau_1)Q_1(s)ds > (2^{\gamma-1})^2 \left( 1 + p_1^\gamma + \frac{p_2^\gamma}{2^{\gamma-1}} \right), \quad (2.2)$$

where

$$Q_i(t) = \min\{q_i(t - \tau_i), q_i(t), q_i(t + \tau_i)\}, \quad (2.3)$$

for  $i = 1, 2$ , then every solution of (1.1) oscillates.

*Proof.* Let  $x$  be a nonoscillatory solution of (1.1). Without loss of generality, we assume that there exists  $t_1 \geq t_0$  such that  $x(t) > 0$ ,  $x(t - \tau_1) > 0$ ,  $x(t + \tau_2) > 0$ ,  $x(t - \sigma_1) > 0$ , and  $x(t + \sigma_2) > 0$  for all  $t \geq t_1$ . Setting

$$\begin{aligned} z(t) &= (x(t) + p_1x(t - \tau_1) + p_2x(t + \tau_2))^\gamma, \\ y(t) &= z(t) + p_1^\gamma z(t - \tau_1) + \frac{p_2^\gamma}{2^{\gamma-1}} z(t + \tau_2). \end{aligned} \quad (2.4)$$

Thus  $z(t) > 0$ ,  $y(t) > 0$ , and

$$z''(t) = q_1(t)x^\gamma(t - \sigma_1) + q_2(t)x^\gamma(t + \sigma_2) \geq 0. \quad (2.5)$$

Then,  $z'(t)$  is of constant sign, eventually. On the other hand,

$$\begin{aligned}
 y''(t) &= q_1(t)x^\gamma(t - \sigma_1) + q_2(t)x^\gamma(t + \sigma_2) \\
 &\quad + p_1^\gamma q_1(t - \tau_1)x^\gamma(t - \tau_1 - \sigma_1) + p_1^\gamma q_2(t - \tau_1)x^\gamma(t - \tau_1 + \sigma_2) \\
 &\quad + \frac{p_2^\gamma}{2^{\gamma-1}} q_1(t + \tau_2)x^\gamma(t + \tau_2 - \sigma_1) \\
 &\quad + \frac{p_2^\gamma}{2^{\gamma-1}} q_2(t + \tau_2)x^\gamma(t + \tau_2 + \sigma_2).
 \end{aligned} \tag{2.6}$$

Note that  $g(u) = u^\gamma$ ,  $\gamma \geq 1$ ,  $u \in (0, \infty)$  is a convex function. Hence, by the definition of convex function, we obtain

$$a^\gamma + b^\gamma \geq \frac{1}{2^{\gamma-1}}(a + b)^\gamma. \tag{2.7}$$

Using inequality (2.7), we get

$$\begin{aligned}
 x^\gamma(t - \sigma_1) + p_1^\gamma x^\gamma(t - \tau_1 - \sigma_1) &\geq \frac{1}{2^{\gamma-1}}(x(t - \sigma_1) + p_1 x(t - \tau_1 - \sigma_1))^\gamma, \\
 \frac{1}{2^{\gamma-1}}(x(t - \sigma_1) + p_1 x(t - \tau_1 - \sigma_1))^\gamma &+ \frac{p_2^\gamma}{2^{\gamma-1}} x^\gamma(t + \tau_2 - \sigma_1) \\
 &\geq \frac{1}{(2^{\gamma-1})^2}(x(t - \sigma_1) + p_1 x(t - \tau_1 - \sigma_1) + p_2 x(t + \tau_2 - \sigma_1))^\gamma = \frac{z(t - \sigma_1)}{(2^{\gamma-1})^2}.
 \end{aligned} \tag{2.8}$$

Similarly, we obtain

$$x^\gamma(t + \sigma_2) + p_1^\gamma x^\gamma(t - \tau_1 + \sigma_2) + \frac{p_2^\gamma}{2^{\gamma-1}} x^\gamma(t + \tau_2 + \sigma_2) \geq \frac{z(t + \sigma_2)}{(2^{\gamma-1})^2}. \tag{2.9}$$

Thus, from (2.6), we have

$$y''(t) \geq \frac{1}{(2^{\gamma-1})^2}(Q_1(t)z(t - \sigma_1) + Q_2(t)z(t + \sigma_2)). \tag{2.10}$$

In the following, we consider two cases.

*Case 1.* Assume that  $z'(t) > 0$ . Then,  $y'(t) > 0$ . In view of (2.10), we see that

$$y''(t + \tau_2) \geq \frac{1}{(2^{\gamma-1})^2} Q_2(t + \tau_2)z(t + \tau_2 + \sigma_2). \tag{2.11}$$

Applying the monotonicity of  $z$ , we find

$$\begin{aligned} y(t + \sigma_2) &= z(t + \sigma_2) + p_1^\gamma z(t - \tau_1 + \sigma_2) + \frac{p_2^\gamma}{2^{\gamma-1}} z(t + \tau_2 + \sigma_2) \\ &\leq \left(1 + p_1^\gamma + \frac{p_2^\gamma}{2^{\gamma-1}}\right) z(t + \tau_2 + \sigma_2). \end{aligned} \quad (2.12)$$

Combining the last two inequalities, we obtain the inequality

$$y''(t + \tau_2) \geq \frac{Q_2(t + \tau_2)}{(2^{\gamma-1})^2 \left(1 + p_1^\gamma + p_2^\gamma/2^{\gamma-1}\right)} y(t + \sigma_2). \quad (2.13)$$

Therefore,  $y$  is a positive increasing solution of the differential inequality

$$y''(t) \geq \frac{Q_2(t)}{(2^{\gamma-1})^2 \left(1 + p_1^\gamma + p_2^\gamma/2^{\gamma-1}\right)} y(t - \tau_2 + \sigma_2). \quad (2.14)$$

However, by [11], condition (2.1) contradicts the existence of a positive increasing solution of inequality (2.14).

*Case 2.* Assume that  $z'(t) < 0$ . Then,  $y'(t) < 0$ . In view of (2.10), we see that

$$y''(t - \tau_1) \geq \frac{1}{(2^{\gamma-1})^2} Q_1(t - \tau_1) z(t - \tau_1 - \sigma_1). \quad (2.15)$$

Applying the monotonicity of  $z$ , we find

$$\begin{aligned} y(t - \sigma_1) &= z(t - \sigma_1) + p_1^\gamma z(t - \tau_1 - \sigma_1) + p_2^\gamma \frac{1}{2^{\gamma-1}} z(t + \tau_2 - \sigma_1) \\ &\leq \left(1 + p_1^\gamma + \frac{p_2^\gamma}{2^{\gamma-1}}\right) z(t - \tau_1 - \sigma_1). \end{aligned} \quad (2.16)$$

Combining the last two inequalities, we obtain the inequality

$$y''(t - \tau_1) \geq \frac{Q_1(t - \tau_1)}{(2^{\gamma-1})^2 \left(1 + p_1^\gamma + p_2^\gamma/2^{\gamma-1}\right)} y(t - \sigma_1). \quad (2.17)$$

Therefore,  $y$  is a positive decreasing solution of the differential inequality

$$y''(t) \geq \frac{Q_1(t)}{(2^{\gamma-1})^2 \left(1 + p_1^\gamma + p_2^\gamma/2^{\gamma-1}\right)} y(t + \tau_1 - \sigma_1). \quad (2.18)$$

However, by [11], condition (2.2) contradicts the existence of a positive decreasing solution of inequality (2.18).  $\square$

*Remark 2.2.* When  $\gamma = 1$ , Theorem 2.1 involves results of [25, Theorem 1].

**Theorem 2.3.** Let  $\beta_i = (\sigma_i - \tau_i)/2 > 0$ ,  $i = 1, 2$ . Suppose that, for  $i = 1, 2$ , there exist functions

$$a_i \in C^1[t_0, \infty), \quad a_i(t) > 0, \quad (-1)^i a'_i(t) \leq 0, \quad (2.19)$$

such that

$$Q_i(t) \geq (2^{\gamma-1})^2 \left( 1 + p_1^\gamma + \frac{p_2^\gamma}{2^{\gamma-1}} \right) a_i(t) a_i(t + (-1)^i \beta_i), \quad (2.20)$$

where  $Q_i$  are as in (2.3) for  $i = 1, 2$ . If the first-order differential inequality

$$v'(t) + (-1)^{i+1} a_i(t + (-1)^i \beta_i) v(t + (-1)^i \beta_i) \geq 0 \quad (2.21)$$

has no eventually negative solution for  $i = 1$  and no eventually positive solution for  $i = 2$ , then (1.1) is oscillatory.

*Proof.* Let  $x$  be a nonoscillatory solution of (1.1). Without loss of generality, we assume that there exists  $t_1 \geq t_0$  such that  $x(t) > 0$ ,  $x(t - \tau_1) > 0$ ,  $x(t + \tau_2) > 0$ ,  $x(t - \sigma_1) > 0$ , and  $x(t + \sigma_2) > 0$  for all  $t \geq t_1$ . Define  $z$  and  $y$  as in Theorem 2.1. Proceeding as in the proof of Theorem 2.1, we get (2.10).

In the following, we consider two cases.

*Case 1.* Assume that  $z'(t) > 0$ . Clearly,  $y'(t) > 0$ . Then, just as in Case 1 of Theorem 2.1, we find that  $y$  is a positive increasing solution of inequality (2.14). Let  $b_2(t) = y'(t) + a_2(t)y(t + \beta_2)$ . Then  $b_2(t) > 0$ . Using (2.19) and (2.20), we obtain

$$\begin{aligned} & b'_2(t) - \frac{a'_2(t)}{a_2(t)} b_2(t) - a_2(t) b_2(t + \beta_2) \\ &= y''(t) - \frac{a'_2(t)}{a_2(t)} y'(t) - a_2(t) a_2(t + \beta_2) y(t + 2\beta_2) \\ &\geq y''(t) - a_2(t) a_2(t + \beta_2) y(t + 2\beta_2) \\ &\geq y''(t) - \frac{Q_2(t)}{(2^{\gamma-1})^2 \left( 1 + p_1^\gamma + \frac{p_2^\gamma}{2^{\gamma-1}} \right)} y(t - \tau_2 + \sigma_2) \geq 0. \end{aligned} \quad (2.22)$$

Define  $b_2(t) = a_2(t)v(t)$ . Then,  $v$  is a positive solution of (2.21) for  $i = 2$ , which is a contradiction.

Case 2. Assume that  $z'(t) < 0$ . Clearly,  $y'(t) < 0$ . Then, just as in Case 2 of Theorem 2.1, we find that  $y$  is a positive decreasing solution of inequality (2.18). Let  $b_1(t) = y'(t) - a_1(t)y(t - \beta_1)$ . Then  $b_1(t) < 0$ . Using (2.19) and (2.20), we obtain

$$\begin{aligned} & b_1'(t) - \frac{a_1'(t)}{a_1(t)}b_1(t) + a_1(t)b_1(t - \beta_1) \\ &= y''(t) - \frac{a_1'(t)}{a_1(t)}y'(t) - a_1(t)a_1(t - \beta_1)y(t - 2\beta_1) \\ &\geq y''(t) - a_1(t)a_1(t - \beta_1)y(t - 2\beta_1) \\ &\geq y''(t) - \frac{Q_1(t)}{(2^{\gamma-1})^2(1 + p_1^\gamma + p_2^\gamma/2^{\gamma-1})}y(t + \tau_1 - \sigma_1) \geq 0. \end{aligned} \tag{2.23}$$

Define  $b_1(t) = a_1(t)v(t)$ . Then,  $v$  is a negative solution of (2.21) for  $i = 1$ . This contradiction completes the proof of the theorem.  $\square$

Remark 2.4. When  $\gamma = 1$ , Theorem 2.3 involves results of [25, Theorem 2].

From Theorem 2.3 and the results given in [12], we have the following oscillation criterion for (1.1).

**Corollary 2.5.** Let  $\beta_i = (\sigma_i - \tau_i)/2 > 0$ ,  $i = 1, 2$ . Assume that (2.19) and (2.20) hold for  $i = 1, 2$ . If

$$\liminf_{t \rightarrow \infty} \int_{t-\beta_1}^t a_1(s - \beta_1) ds > \frac{1}{e}, \tag{2.24}$$

$$\liminf_{t \rightarrow \infty} \int_t^{t+\beta_2} a_2(s + \beta_2) ds > \frac{1}{e}, \tag{2.25}$$

then (1.1) is oscillatory.

*Proof.* It is known (see [12]) that condition (2.24) is sufficient for inequality (2.21) (for  $i = 1$ ) to have no eventually negative solution. On the other hand, condition (2.25) is sufficient for inequality (2.21) (for  $i = 2$ ) to have no eventually positive solution.  $\square$

For an application of our results, we give the following example.

Example 2.6. Consider the second-order differential equation

$$[(x(t) + p_1x(t - \tau_1) + p_2x(t + \tau_2))^\gamma]'' = q_1x^\gamma(t - \sigma_1) + q_2x^\gamma(t + \sigma_2), \quad t \geq t_0, \tag{2.26}$$

where  $q_i > 0$  are constants and  $\sigma_i > \tau_i$  for  $i = 1, 2$ .

It is easy to see that  $Q_i(t) = q_i$ ,  $i = 1, 2$ . Assume that  $\varepsilon > 0$ . Let  $a_i(t) = (2 + \varepsilon)/(e(\sigma_i - \tau_i))$ ,  $i = 1, 2$ . Clearly, (2.19) holds. If

$$q_i > \left[ \frac{2}{(e(\sigma_i - \tau_i))} \right]^2 (2^{\gamma-1})^2 \left( 1 + p_1^\gamma + \frac{p_2^\gamma}{2^{\gamma-1}} \right) \quad (2.27)$$

for  $i = 1, 2$ , then (2.20) holds. Moreover, we see that

$$\begin{aligned} \liminf_{t \rightarrow \infty} \int_{t-\beta_1}^t a_1(s - \beta_1) ds &= \frac{2 + \varepsilon}{2e} > \frac{1}{e}, \\ \liminf_{t \rightarrow \infty} \int_t^{t+\beta_2} a_2(s + \beta_2) ds &= \frac{2 + \varepsilon}{2e} > \frac{1}{e}. \end{aligned} \quad (2.28)$$

Hence by applying Corollary 2.5, we find that (2.26) is oscillatory.

## Acknowledgments

The authors sincerely thank the referees for their constructive suggestions which improved the content of the paper. This research is supported by the Natural Science Foundation of China (11071143, 60904024, 11026112), China Postdoctoral Science Foundation funded project (200902564), and Shandong Provincial Natural Science Foundation (ZR2010AL002, ZR2009AL003, Y2008A28); it was also supported by University of Jinan Research Funds for Doctors (XBS0843).

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