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HAL Id: hal-01418212
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Submitted on 6 Jan 2017

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Migration of imaginary roots of multiplicity three and four under small deviation of two delays in time-delay systems

Dina Irofti, Keqin Gu, Islam Boussaada, and Silviu-Iulian Niculescu

Abstract—This paper studies the migration pattern of characteristic imaginary roots of multiplicity three and four in time-delay systems with two delays when the delay parameters undergo small deviations. Stability analysis for such problems is often based on Puiseux series, as multiple roots are not differentiable with respect to delay parameters. However, in this paper the approach is more traditional without using Puiseux series. In the case of triple roots, we show that the stability crossing curves are smooth; when a perturbation occurs in the delay parameter space, two roots move to one half-plane and one root to the other half-plane. The case of quadruple root is more complicated as the stability crossing curve has a cusp. Thus, in the neighbourhood of the critical point, the root is more complicated as the stability crossing curve has a cusp as shown in Figure 1, and an explicit deviation of two delays in time-delay systems

Consider a system with two delays, $\tau_1$ and $\tau_2$, with the characteristic equation

$$p(s, \tau_1, \tau_2) = p_0(s) + p_1(s)e^{-\tau_1 s} + p_2(s)e^{-\tau_2 s} = 0,$$

where $p_k(s)$, $k = 0, 1, 2$ are polynomials of $s$ with real coefficients, $\tau_1$, $\tau_2$ are independent positive delays, and $s$ is the Laplace variable. For $\tau_1 = \tau_{10}$, $\tau_2 = \tau_{20}$, we assume $p(s, \tau_1, \tau_2)$ has an imaginary root $s_0 = i\omega_0$ of $m^{th}$ order. In other words,

$$\frac{\partial^k p}{\partial s^k} \bigg|_{s=s_0, \tau_1=\tau_{10}, \tau_2=\tau_{20}} = 0, \text{ for } k = 0 \ldots m - 1$$

and

$$\frac{\partial^m p}{\partial s^m} \bigg|_{s=s_0, \tau_1=\tau_{10}, \tau_2=\tau_{20}} \neq 0.$$

The case of $m = 2$ (double roots) is presented in [9]. This paper studies the case of $m = 3$ (triple roots) and $m = 4$ (quadruple roots).
Throughout this paper, we make the following “least degeneracy” assumption:
\[
D = \det \begin{pmatrix} \text{Re}(\frac{\partial p}{\partial \tau_1}) & \text{Re}(\frac{\partial p}{\partial \tau_2}) \\ \text{Im}(\frac{\partial p}{\partial \tau_1}) & \text{Im}(\frac{\partial p}{\partial \tau_2}) \end{pmatrix} \neq 0,
\]
where \(\text{Re}(\cdot)\) denotes the real part, and \(\text{Im}(\cdot)\) denotes the imaginary part of a complex number. In view of implicit function theorem, a consequence of the assumption (4) is that the characteristic equation (1) defines the pair \((\tau_1, \tau_2)\) in a small neighbourhood of the critical point \((\tau_{10}, \tau_{20})\) as a function of \(s\) in a sufficiently small neighbourhood of \(s_0\).

Introduce the notation
\[
\mathcal{N}_c(x_0) = \{ x \mid |x - x_0| < \varepsilon \}.
\]
Then, in a sufficiently small neighbourhood \(\mathcal{N}_c(s_0)\) of \(s_0\), we can define (see proposition 1 in [9]) two functions, \(\tau_1(s)\) and \(\tau_2(s)\), differentiable up to an arbitrary order, as the unique solution of characteristic equation (1) in a small neighbourhood, \((\tau_1(s), \tau_2(s)) \in \mathcal{N}_c(\tau_{10}, \tau_{20})\) (but this characteristic equation may have other solutions outside the of \(\mathcal{N}_c(\tau_{10}, \tau_{20})\)).

Define local stability crossing curve as the set
\[
\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}^+ = \{(\tau_1(i\omega), \tau_2(i\omega)) \mid \omega \in \mathcal{N}_\delta(i\omega_0), \omega > \omega_0 \}
\]
This curve divides \(\mathcal{N}_c(\tau_{10}, \tau_{20})\) into two regions. We will study how the triple or quadruple roots migrate as the delay parameters \((\tau_1, \tau_2)\) move into one of these two regions.

For the sake of convenience, we also define the positive local stability crossing curve as
\[
\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}^+ = \{(\tau_1(i\omega), \tau_2(i\omega)) \mid \omega \in \mathcal{N}_\delta(i\omega_0), \omega > \omega_0 \}
\]
and the negative local stability crossing curve as
\[
\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}^- = \{(\tau_1(i\omega), \tau_2(i\omega)) \mid \omega \in \mathcal{N}_\delta(i\omega_0), \omega < \omega_0 \}.
\]

### III. MULTIPlicity THREE

In this section, we study the migration of triple roots.

**Theorem 1:** Suppose system (1) satisfies (2) and (3) for \(m = 3\), and assumption (4) holds. Then, as \((\tau_1, \tau_2)\) moves from \((\tau_{10}, \tau_{20})\) to one of the two regions of \(\mathcal{N}_c(\tau_{10}, \tau_{20})\) divided by \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}^+\), at least one root moves to the right half-plane, and one other root moves to the left half-plane. The remaining root may move to either the left half-plane, or the right half-plane. Specifically:

**Case i.** \(D > 0\) and \((\tau_1, \tau_2)\) moves in the region on the clockwise side of \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}^+\) and on the counterclockwise side of \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}^-\). In this case, two characteristic roots of (1) move to the right-half complex plane, and the third root moves to the left-half plane.

**Case ii.** \(D > 0\) and \((\tau_1, \tau_2)\) moves in the region on the clockwise side of \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}^-\) and on the counterclockwise side of \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}^+\). In this case, two characteristic roots of (1) move to the left-half complex plane, and the third root moves to the right-half plane.

**Case iii.** \(D < 0\) and \((\tau_1, \tau_2)\) moves in the region on the clockwise side of \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}^-\) and on the counterclockwise side of \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}^+\). In this case, two characteristic roots of (1) move to the right-half complex plane, and the third root moves to the left-half plane.

**Case iv.** \(D < 0\) and \((\tau_1, \tau_2)\) moves in the region on the clockwise side of \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}^+\) and on the counterclockwise side of \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}^-\). In this case, two characteristic roots of (1) move to the left-half complex plane, and the third root moves to the right-half plane.

**Proof:** In the complex plane consider a point \(s\) in the neighbourhood of \(s_0\), let
\[
s = s_0 + u e^{i\theta}.
\]

Denote
\[
\gamma = e^{i\theta} = \frac{\partial s}{\partial u}.
\]

Differentiate (1) with respect to \(u\) with the angular variable \(\theta\) fixed (equivalently with \(\gamma\) fixed), and consider \(\tau_1(s)\) and \(\tau_2(s)\) as functions of \(u\) and \(\theta\). This yields:
\[
\frac{\partial p}{\partial \tau_1} + \frac{\partial p}{\partial \tau_2} + \frac{\partial p}{\partial s} \gamma = 0.
\]

Setting \(u = 0\) and using equation (2) for \(k = 1\) in (6), we obtain
\[
\left( \begin{array}{c} \text{Re} \left( \frac{\partial p}{\partial \tau_1} \right) \\ \text{Im} \left( \frac{\partial p}{\partial \tau_1} \right) \end{array} \right) \bigg|_{u = 0} = 0,
\]
from which we conclude
\[
\left( \begin{array}{c} \frac{\partial \tau_1}{\partial u} \\ \frac{\partial \tau_2}{\partial u} \end{array} \right) \bigg|_{u = 0} = 0,
\]
in view of (4) and (5).

Differentiating (6) with respect to \(u\) again yields
\[
\frac{\partial^2 p}{\partial \tau_1^2} \left( \frac{\partial \tau_1}{\partial u} \right)^2 + 2 \frac{\partial^2 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_1}{\partial u} \frac{\partial \tau_2}{\partial u} + 2 \frac{\partial^2 p}{\partial \tau_1 \partial s} \frac{\partial \tau_1}{\partial u} \frac{\partial s}{\partial u} + \frac{\partial p}{\partial \tau_1} \frac{\partial^2 \tau_1}{\partial u^2} + \frac{\partial p}{\partial \tau_2} \frac{\partial^2 \tau_2}{\partial u^2} + \frac{\partial p}{\partial \tau_1} \frac{\partial^2 \tau_2}{\partial u \partial s} + \frac{\partial p}{\partial \tau_2} \frac{\partial^2 \tau_1}{\partial u \partial s} = 0.
\]

Similar to the way we obtained (7) from (6), we may conclude from (8) using (2) for \(k = 2\) and equation (7) that
\[
\left( \begin{array}{c} \frac{\partial^2 \tau_1}{\partial u^2} \\ \frac{\partial^2 \tau_2}{\partial u^2} \end{array} \right) \bigg|_{u = 0} = 0.
\]
Differentiating (8) again with respect to $u$ yields
\[
\frac{\partial^3 p}{\partial u^3} \left( \frac{\partial \tau_1}{\partial u} \right)^3 + 3 \frac{\partial^2 p}{\partial \tau_1^2} \frac{\partial \tau_1}{\partial u} + \\
+3 \left( \frac{\partial^2 p}{\partial \tau_1 \partial \tau_2} \right) \left( \frac{\partial \tau_2}{\partial u} \right)^2 + 3 \frac{\partial^2 p}{\partial \tau_1^2} \frac{\partial \tau_2}{\partial u} + \\
+3 \frac{\partial^2 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_1}{\partial u} + 6 \frac{\partial^3 p}{\partial \tau_1 \partial \tau_2 \partial u} + \\
+3 \left( \frac{\partial^3 p}{\partial \tau_1 \partial \tau_2^2} \right) \left( \frac{\partial \tau_2}{\partial u} \right) \gamma + \\
+3 \frac{\partial^3 p}{\partial \tau_1 \partial \tau_2^2} \frac{\partial \tau_2}{\partial u} + 6 \frac{\partial^2 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_2}{\partial u} \gamma + \\
+3 \frac{\partial^3 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_1}{\partial u} + 6 \frac{\partial^2 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_1}{\partial u} \gamma + \\
+3 \frac{\partial^3 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_2}{\partial u} \gamma^2 + 3 \frac{\partial^2 p}{\partial \tau_2 \partial \tau_3} \frac{\partial \tau_2}{\partial u} \gamma^2 + \\
+3 \frac{\partial^3 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_1}{\partial u} \gamma^2 + 3 \frac{\partial^2 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_1}{\partial u} \gamma^2 + \\
+3 \frac{\partial^3 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_2}{\partial u} \gamma^2 + 3 \frac{\partial^2 p}{\partial \tau_2 \partial \tau_3} \frac{\partial \tau_2}{\partial u} \gamma^2 + \\
+3 \frac{\partial^3 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_1}{\partial u} \gamma^2 + 3 \frac{\partial^2 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_1}{\partial u} \gamma^2 + \\
+3 \frac{\partial^3 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_2}{\partial u} \gamma^2 + 3 \frac{\partial^2 p}{\partial \tau_2 \partial \tau_3} \frac{\partial \tau_2}{\partial u} \gamma^2 + \\
+3 \frac{\partial^3 p}{\partial \tau_1 \partial \tau_2} \frac{\partial \tau_1}{\partial u} \gamma^2 = 0.
\]

If we set $u = 0$ and use (7) and (9) in equation (10), we obtain
\[
\left( \frac{\partial p}{\partial \tau_1} \frac{\partial \tau_1}{\partial u} + \frac{\partial p}{\partial \tau_2} \frac{\partial \tau_2}{\partial u} + \frac{\partial p}{\partial \tau_3} \frac{\partial \tau_3}{\partial u} \gamma \right) \bigg|_{s = s_0, \tau_1 = \tau_{10}, \tau_2 = \tau_{20}} = 0
\]

or
\[
\left( \frac{\partial p}{\partial \tau_1} \frac{\partial \tau_1}{\partial u} + \frac{\partial p}{\partial \tau_2} \frac{\partial \tau_2}{\partial u} + \frac{\partial p}{\partial \tau_3} \frac{\partial \tau_3}{\partial u} \gamma \right) \bigg|_{s = s_0, \tau_1 = \tau_{10}, \tau_2 = \tau_{20}} = \left( \frac{\partial^3 p}{\partial s^3 \gamma} \right) \bigg|_{s = s_0, \tau_1 = \tau_{10}, \tau_2 = \tau_{20}}.
\]

We separate real and imaginary part to obtain
\[
\begin{pmatrix}
\text{Re} \left( \frac{\partial \tau_1}{\partial u} \right) \\
\text{Im} \left( \frac{\partial \tau_1}{\partial u} \right)
\end{pmatrix}
\bigg|_{s = s_0, \tau_1 = \tau_{10}, \tau_2 = \tau_{20}} = -\begin{pmatrix}
\text{Re} \left( \frac{\partial^3 \tau_1}{\partial s^3 \gamma} \right) \\
\text{Im} \left( \frac{\partial^3 \tau_1}{\partial s^3 \gamma} \right)
\end{pmatrix}
\bigg|_{s = s_0, \tau_1 = \tau_{10}, \tau_2 = \tau_{20}}.
\]

Thus
\[
\begin{pmatrix}
\frac{\partial^3 \tau_1}{\partial s^3 \gamma} \\
\frac{\partial^3 \tau_2}{\partial s^3 \gamma}
\end{pmatrix}
\bigg|_{s = s_0, \tau_1 = \tau_{10}, \tau_2 = \tau_{20}} = -\begin{pmatrix}
\text{Re} \left( \frac{\partial^3 \tau_1}{\partial s^3 \gamma} \right) \\
\text{Im} \left( \frac{\partial^3 \tau_1}{\partial s^3 \gamma} \right)
\end{pmatrix}
\bigg|_{s = s_0, \tau_1 = \tau_{10}, \tau_2 = \tau_{20}}.
\]

Using Lemma 6 in [9] and in view of (11), we know that a 90° counterclockwise rotation of $\gamma$ in the complex plane will generate a 270° rotation in the parameter space, in the counterclockwise direction if $D > 0$, and in the clockwise direction if $D < 0$.

Accounting for higher order terms, the situation is illustrated in Figure 2 for Cases i and ii ($D > 0$), and in Figure 3 for Cases iii and iv ($D < 0$). In both Figures 2 and 3, the line segment $CD$ in the diagram on the left is mapped to $C'D'$ in the diagram on the right. Similarly, $CB$, $CE$ and $CA$ in the diagram on the left are mapped to $C'B'$ (in Im$(+)$) or $T_{(\omega_0, \tau_{10} - \tau_{20})}$, $C'E'$ (in Re$(-)$) and $C'A'$ (in Im$(-)$) or $T_{(\omega_0, \tau_{10} - \tau_{20})}$ in the diagram on the right.

Consider Cases i and ii shown in Figure 2. The arc $BD$ in darker solid curve on the diagram on the left is mapped to the arc $B'D'$ in the same line type on the diagram on the right that goes around point $C'$ about $270^\circ$. Therefore, region I bounded by $BC$, $CD$, and arc $DB$ in the diagram on the left is mapped bijectively to the singly connected region bounded by the arcs $B'C'$, $C'D'$ and the darker solid arc $D'B'$, which we will denote as $I'$, in the diagram on the right. Similarly, region II is mapped bijectively to region $II'$ bounded by $E'C'$, $C'B'$ and the darker dotted arc $B'E'$, region III is mapped bijectively by region $III'$ bounded by $A'C'$, $C'E'$ and the lighter solid arc $E'A'$, region IV is mapped bijectively to region $IV'$ bounded by $D'C'$, $C'A'$ and the lighter dotted arc $A'D'$. Notice, the region on the clockwise side of Im$(-)$ (or $T_{(\omega_0, \tau_{10} - \tau_{20})}$) and on the counterclockwise side of Im$(+)$ (or $T_{(\omega_0, \tau_{10} - \tau_{20})}$) in the neighbourhood of $C'$ (or $(\tau_{10}, \tau_{20})$) may be expressed as $I' \cap (III' \cup III') \cap IV'$. Therefore, for any $(\tau_1, \tau_2)$ in this region, there must be one root in region I, one root in either region II or region III, and one root in region IV. In other words, there must be two roots on the right half plane, and one root on the left half plane. This proves Case i. Case ii can be shown by noticing that the region on the clockwise side of Im$(-)$ (or $T_{(\omega_0, \tau_{10} - \tau_{20})}$) and on the counterclockwise side of Im$(+)$ (or $T_{(\omega_0, \tau_{10} - \tau_{20})}$) in the neighbourhood of $(\tau_{10}, \tau_{20})$ may be expressed as $(I' \cup IV') \cap III' \cap IV'$. Cases iii and iv may be shown similarly.

**Remark 1:** Note that
\[
\frac{\partial^3 \tau_1}{\partial s^3 \gamma} = -\frac{\partial^3 \tau_1}{\partial s^3 \gamma}
\]
in view of (11). This means, in view of (7) and (9), that $T_{(\omega_0, \tau_{10} - \tau_{20})}$ has the same tangent as $T_{(\omega_0, \tau_{10} - \tau_{20})}$ at $(\tau_{10}, \tau_{20})$. Thus, $T_{(\omega_0, \tau_{10} - \tau_{20})}$ is a smooth curve. In other words, unlike the double root case discussed in [9], the stability crossing
The mapping \((\tau_1(s), \tau_2(s))\) in a neighborhood of \(s_0\), \(D > 0\).

IV. MULTIPLICITY FOUR

In this section we study the migration of quadruple roots. For system (1), \(s_0\) is a quadruple root if conditions (2) and (3) hold for \(m = 4\).

Parameterize \(s\) by \(u\) and \(\theta\) (or \(\gamma\)) as in (5). From (7), (9) and (11), we immediately conclude

\[
\begin{align*}
\left(\frac{\partial^4 p}{\partial \tau_1^4} + \frac{\partial^4 p}{\partial \tau_2^4} \frac{\partial^2 p}{\partial u^4}\right)_{u=0} & = 0 \quad \text{for } k = 1, 2, 3.
\end{align*}
\]

The above is true for \(k = 3\) due to (11) and equation (2) for \(k = 3\).

Differentiate (10) again with respect to \(u\), taking into account (12); we obtain

\[
\begin{align*}
\left(\frac{\partial^4 p}{\partial \tau_1^4} + \frac{\partial^4 p}{\partial \tau_2^4} \frac{\partial^2 p}{\partial u^4}\right)_{u=0} & = -\left(s = s_0\right)_{\tau = \tau_0} \left(s = s_0\right)_{\tau = \tau_2}.
\end{align*}
\]

This can be solved to obtain

\[
\begin{align*}
\left(\frac{\partial^4 p}{\partial \tau_1^4} + \frac{\partial^4 p}{\partial \tau_2^4} \frac{\partial^2 p}{\partial u^4}\right)_{s = s_0} & = \frac{\text{Re}}{\text{Im}} \left(\frac{\partial^3 p}{\partial \tau_1^3}ight) \left(\frac{\partial^3 p}{\partial \tau_2^3}ight)^{-1} \left(\frac{\partial^3 p}{\partial \tau_1^3 \tau_2^3}ight). 
\end{align*}
\]

Similar to the triple root case, the last equation above shows that \(\left(\frac{\partial^4 p}{\partial \tau_1^4} + \frac{\partial^4 p}{\partial \tau_2^4} \frac{\partial^2 p}{\partial u^4}\right)_{\gamma = \gamma} \) rotates four times as fast as \(\gamma\) does. To understand this case, we shall divide the circle in \(s\) domain in \(45^\circ\) pieces in the complex plane, in order to work with singly connected regions (see Figures 4 to 7, left).

Considering (12) and (13) for \(\gamma = i\) and \(\gamma = -i\), we see that the local stability crossing curve \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}\) have a cusp at \((\tau_{10}, \tau_{20})\) [17]. Indeed, \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}\) partitions a sufficiently small neighborhood of \((\tau_{10}, \tau_{20})\) into a great sector (or G-sector) and a small sector (or S-sector) as shown in Figure 1. Next theorem shows how the quadruple roots at \(\omega_0\) migrate as \((\tau_1, \tau_2)\) moves from \((\tau_{10}, \tau_{20})\) to the G-sector or the S-sector.

**Theorem 2:** Suppose system (1) satisfies (2) and (3) for \(m = 4\), and assumption (4) holds.

If \((\tau_1, \tau_2)\) is in the G-sector in a sufficiently small neighborhood of \((\tau_{10}, \tau_{20})\), then two roots of (1) in the neighborhood of \(s_0\) are in the right half-plane, and the other two are in the left half-plane.

When \((\tau_1, \tau_2)\) is in the S-sector, then three roots move into one half-plane, and the fourth one moves into the other half-plane. More precisely,

**Case i.** If \(D > 0\), and \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}\) is in the counterclockwise side of \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}\) in the S-sector, then three roots are in the left half-plane, and one root is in the right half-plane.

**Case ii.** If \(D > 0\), and \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}\) is in the clockwise side of \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}\) in the S-sector, then three roots are in the right half-plane, and one root is in the left half-plane.

**Case iii.** If \(D < 0\), and \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}\) is in the counterclockwise side of \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}\) in the S-sector, then three roots are in the right half-plane, and one root is in the left half-plane.

**Case iv.** If \(D < 0\), and \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}\) is in the clockwise side of \(\mathcal{T}_{(\omega_0, \tau_{10}, \tau_{20})}\) in the S-sector, then three roots are in the left half-plane, and one root is in the right half-plane.

**Proof:** Denote the sector \(ACE\) in the left-hand side of Figures 4-7 by region \(I\). In the same manner, region \(II\) the sector \(EFC\), region \(III\) the sector \(FCG\), and so on.

Thus, the neighbourhood of \(s_0\) shown in left side of Figures 4 to 7 as a disk centered in \(C\) is divided into 8 regions, denoted by \(I, II, \ldots, VIII\). The mapping of these regions to \(\tau_{1}-\tau_{2}\) parameter space is represented in the right side of the figures. Note that we obtain another 8 singly connected regions: region \(I'\) is bounded by curves \(A'C', C'E'\) and \(A'E'\), region \(II'\) by \(C'E', E'F'\) and \(F'C'\), and so on.

The neighbourhood \(\mathcal{N}_s(\tau_{10}, \tau_{20})\) is divided into S-sector and G-sector by the curves \(A'C'\) and \(B'C'\). In general, \(F'\) and \(I'\) each may be either in the S-sector, or in the G-sector. We shall only show the case where they are in the S-sector. Their location do not affect the validity of the conclusion. When one or both points \(F'\) and \(I'\) are outside of the S-sector, the proof for the G-sector is slightly more involved, but still possible.

Similar to the case discussed in [9] (see corollary 4) we can show that \((\tau_i(s), \tau_j(s))\) is a bijection from \(R\) to \(R'\) when \(s\) is restricted to \(R\), with \(R\) a region from the set \(\{I, II, \ldots, VIII\}\), and \(R'\) the corresponding region in the
set \{I', II', \ldots, VIII'\}.

Consider Case i. The S-sector (in a sufficiently small neighbourhood) can be expressed as \((II' \cup III') \cap V' \cap (VI' \cup VII') \cap VIII'\), as depicted in Figure 4 right. But the corresponding regions are \((II \cap III)\), which is in the right-half plane, and \(V' \cup VI' \cup VII' \cap VIII,\) which are all in the left-half plane. So we may conclude that when \((\tau_1, \tau_2)\) is in the S-sector, the characteristic equation (1) has a root in the right-half plane, and three others in the left-half plane. As for the G-sector, Figure 4 shows that it can be expressed as \((II' \cap III') \cap (III' \cup IV') \cap (VI' \cap VII') \cap VIII'\). Thus, the characteristic equation (1) has two unstable roots in G-sector, within the regions \((I' \cup II)\) and \((III' \cup IV)\), and two stable roots, within the regions \((V' \cup VI)\) and \((VI' \cup VII)\).

Case ii: The S-sector can be expressed as \(I'\cap (II' \cup III') \cap IV' \cap (VI' \cup VII')\), as shown in Figure 5. Therefore, for any \((\tau_1, \tau_2)\) in S-sector, one characteristic root must be in \((VI \cup VII)\) (in the left half-plane), and the remaining three roots in right half-plane (one in I, one in II, and one in IV). Next, G-sector can be expressed as \((I' \cap II') \cap (III' \cup IV') \cap (VI' \cup VII) \cap (VII' \cup VIII)\). Therefore, we can conclude that there are two roots on the left-half plane and two roots on the right-half plane.

For case iii and case iv, the conclusions can be drawn in a similar manner. Case iii is illustrated in Figure 6. S-sector can be expressed as \(I'\cap (II' \cap III') \cap IV' \cap (VI' \cup VII')\), and G-sector as \((I' \cup II') \cap (III' \cup IV') \cap (VI' \cup VII') \cap (VII' \cup VIII)\). Case iv is depicted in Figure 7. S-sector can be expressed as \((II' \cup III') \cap IV' \cap (VI' \cup VII') \cap (VII' \cup VIII')\), and G-sector as \((I' \cup II') \cap (III' \cup IV') \cap (VI' \cup VII') \cap (VII' \cup VIII')\).

V. ILLUSTRATIVE EXAMPLE

Consider the quasi-polynomial

\[
p(s, \tau_1, \tau_2) = s^4 + a_{03}s^3 + a_{02}s^2 + a_{01}s + a_{00} + a_{12}s^2 + a_{11}s + a_{10}e^{-s\tau_1} + a_{21}s + a_{20}e^{-s\tau_2}.
\]

The system has a triple imaginary root at \(s = s_0 = i\omega_0\), with \(\omega_0 = 1\), for \((\tau_1, \tau_2) = (3, 5)\), \(a_{03} = 1, a_{12} = 1, a_{21} = 1,\) and the values of other coefficients are given in table I, where \(s_k\) stands for \(\sin k\), and \(c_k\) stands for \(\cos k\).

As depicted in Figure 8, the local stability crossing curves divide the neighbourhood of \((3, 5)\) in the \(\tau_1-\tau_2\) plane into two regions. Next, it can be calculated that \(D > 0\). Therefore, for \((\tau_1, \tau_2)\) taking values in the region below the curve, which is on the clockwise side of \(T_{(\omega_0, \tau_1, \tau_2)}\) and on the counterclockwise side of \(T_{(\omega_0, \tau_1, \tau_2)}\), two roots will move in the left-half plane, and one root in the right-half plane. Similarly, for \((\tau_1, \tau_2)\) taking values above the curve, two roots will move on the right-half plane, and one root on the left-half plane.

VI. CONCLUSIONS

The migration of imaginary characteristic roots of multiplicity three and four in time-delay systems under the deviation of two delay parameters can be studied by using a conventional approach, without using Puiseux series.

Under the least degeneracy assumption, neither the triple
As shown in Table I, the coefficients’ values for illustrative example.

In the case of quadruple roots, the stability crossing curve has a cusp and divides the neighbourhood of \( (\tau_1, \tau_2) \) into a S-sector and a G-sector. When the delay parameters move into the G-sector, there are two roots on the right-half plane and the other two on the left-half plane. When the delay parameters move into the S-sector, either there are three right-half plane roots and one left-half plane root, or there are three left-half plane roots and one right-half plane root.

**ACKNOWLEDGMENT**

We would like to thank the anonymous reviewers for their suggestions and comments. Part of the work was completed while Keqin Gu was visiting L2S. The financial support for this visit was provided by the RTRA Digiteo network in Paris-Saclay area.

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