Perspective

The Distribution of Zeros of Quasi-Polynomials

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PROFESSOR Yitang Zhang, a number theorist at the University of California, Santa Barbara, USA, has posted a paper on arXiv [1] that hints at the possibility that he may have solved the Landau-Siegel zeros conjecture. He has claimed that he has disproved a weaker version of the Landau-Siegel zeroes conjecture, an important problem related to the hypothesis. The conjecture is that there are solutions to the zeta function that do not assume the form prescribed by the Riemann hypothesis. Inspired by his work, in this *Perspective*, we would like to discuss about the distribution of zeros of quasi-polynomials for linear time-invariant (LTI) systems with time delays.

The stability and dynamic performance of an LTI system depend on its eigenvalue location, i.e., the location of zeros of its characteristic function. An LTI system is asymptotically stable if and only if all its eigenvalues are located in the open left-half complex plane. Therefore, analysis of the performance of an LTI system via determination of the eigenvalue location is an important way by applying a frequency-domain method. Moreover, one can design an LTI control system via assigning the zeros of its characteristic function to the desired positions, which is known as eigenvalue assignment [2].

For an LTI system, one usually considers the eigenvalues in the open right-half complex plane due to the fact that such eigenvalues have a direct influence on the stability of the system. The characteristic function of an LTI system without time delay is a polynomial. One can analyze the distribution of zeros of a polynomial by applying some mathematic tools including the Routh-Hurwitz criterion, Nyquist plot, root locus, and so forth [2]. These tools can not only judge the stability of such an LTI system but also determine the number of zeros of the characteristic function in the open right-half complex plane. In addition, one can obtain the location of the zeros by numerical computation because the number of zeros of a polynomial is finite.

A time-delay system is also called a system with after-effect or dead-time [3]. Time-delay systems have received considerable attention due to the fact that time delays exist in a wide range of practical applications, including networked control systems, vehicular traffic flow, and biology [4]–[6]. Time-delay systems are a class of *infinite dimensional systems*, which have complicated dynamic properties compared with delay-free systems. For an LTI time-delay system, the location of zeros of the characteristic function plays a significant role in analysis and synthesis of the system [7]–[9]. However, it should be pointed out that determination of the distribution of zeros of the characteristic function has always been a difficult issue [10].

The characteristic functions of LTI time-delay systems can be described by a class of quasi-polynomials [11]. Over the last decade, we have conducted research on the distribution of zeros of the quasi-polynomials for LTI time-delay systems and derived some results on revealing information about the distribution of zeros of quasi-polynomials with real coefficients and the design of PID type controllers via dominant eigenvalue assignment for LTI systems with single delay [12], [13]. Based on our own experience and results in the literature over the past decades, we would like to present some problems on the distribution of zeros of quasi-polynomials for LTI time-delay systems.

A large class of models of LTI systems with lumped delays can be described by a differential difference equation in the form of

$$\sum_{k=0}^{q} C_k\dot{\mathrm{x}}(t-\tau_k)=\sum_{k=0}^{q} A_k\mathrm{x}(t-\tau_k), \tag{1}$$

where x is the n-dimensional state variable, A_k, C_k with $k=0, 1,\ldots,q$ are given $n\times n$ real (or complex) constant matrices, $0=\tau_0<\tau_1<\cdots<\tau_q$ are time delays, and $q\geq 1$, or in the form of

$$\sum_{k=0}^{m}\sum_{j=0}^{n} a_{k,j}\mathrm{x}^{(j)}(t-\tau_k)=0, \tag{2}$$

where x is a system variable, $a_{k,j},\ j=0,1,\ldots,n,\ k=0,1,\ldots,m$, are real (or complex) constant numbers, and $0=\tau_0<\tau_1<\cdots<\tau_m$ are time delays. The characteristic function of (1) or (2) can be described by a quasi-polynomial as

$$\delta(s)=\sum_{k=0}^{m}\sum_{j=0}^{n}\alpha_{k,j}s^j e^{-\tau_k s}, \tag{3}$$

where s is a complex variable, $\alpha_{k,j},\ j=0,1,\ldots,n,\ k=0,1,\ldots,m$, are real (or complex) constant numbers, and $m=qn$.

This *Perspective* is concerned with the following questions: *1) How can one determine whether or not all the zeros of the quasi-polynomial* (3) *are located in the open left-half complex plane? and 2) If there exist some zeros of the quasi-polynomial* (3) *in the open right-half complex plane, how can one determine the number of zeros?*

Determining the distribution of zeros of the quasi-polynomial (3) by *direct calculation* is difficult because the inclusion of delays leads to an infinite-dimensional function which has *an infinite number of zeros*. Over the past decades, several mathematical methods and techniques for analyzing the distribution of zeros of different types of the quasi-polynomial (3) have been developed. It is necessary for us to introduce some types of the quasi-polynomial (3).

(i) Commensurate and Incommensurate Delays

For the delay parameters in the quasi-polynomial (3), τ_k, $k=0,1,\ldots,m$, they are called *commensurate* if there exists a positive real number τ which leads to

$$\tau_k=\phi_k\tau,\ \ k=0,1,\ldots,m, \tag{4}$$

where ϕ_k is a nonnegative integer number. Otherwise, the delays are

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called *incommensurate*.

(ii) Retarded Type and Neutral Type

For (3), if $\alpha_{0,n} \neq 0$ and $\alpha_{1,n} = \alpha_{2,n} = \cdots = \alpha_{m,n} = 0$, it reduces to a quasi-polynomial of retarded type. Otherwise, if $\alpha_{0,n} \neq 0$ and at least one of $\alpha_{k,n} \neq 0$, $k = 1, 2, \ldots, m$, the corresponding characteristic function is a quasi-polynomial of neutral type.

If τ_k, $k = 0, 1, \ldots, m$ in (3) are commensurate, the quasi-polynomial can be written as

$$\mathcal{H}(\lambda) = \delta\left(\frac{\lambda}{\tau}\right) = \sum_{k=0}^{M}\sum_{j=0}^{N}\beta_{k,j}\lambda^j e^{-k\lambda}, \tag{5}$$

by substituting $s = \frac{\lambda}{\tau}$ into $\delta(s)$, where λ is a complex variable, $\beta_{k,j}$, $j = 0, 1, \ldots, N$, $k = 0, 1, \ldots, M$, are real (or complex) constant numbers, $M = \phi_m$ and $N = n$. Note that $\delta(s)$ and $\mathcal{H}(\lambda)$ have the same number of zeros in the open left-half complex plane, in the open right-half complex plane, and on the imaginary axis, respectively, because τ is a positive real number. Then, multiplying $\mathcal{H}(\lambda)$ by $e^{M\lambda}$, we have a function $H(\lambda)$ in the form of

$$H(\lambda) = e^{M\lambda}\mathcal{H}(\lambda) = \sum_{k=0}^{M}\sum_{j=0}^{N}\gamma_{k,j}\lambda^j e^{k\lambda}, \tag{6}$$

where $\gamma_{k,j}$, $j = 0, 1, \ldots, N$, $k = 0, 1, \ldots, M$, are real (or complex) constant numbers. Here, $H(\lambda)$ is also a quasi-polynomial [11]. It should be pointed out that the location of zeros of the quasi-polynomial $H(\lambda)$ is the same as that of $\mathcal{H}(\lambda)$ since the term $e^{M\lambda} \neq 0$ in the whole complex plane. Therefore, one can exactly analyze the stability and instability of an LTI system with commensurate delays through the location of zeros of the quasi-polynomial $H(\lambda)$ in (6), which is the work by Pontryagin in 1942 [14]. The main results derived by Pontryagin are listed as follows.

Theorem 1: Let $H(\lambda)$ be a quasi-polynomial in the form (6) with $\gamma_{NM} \neq 0$. Write

$$H(i\omega) = H_r(\omega) + iH_i(\omega), \tag{7}$$

where ω is a real number, and $H_r(\omega)$ and $H_i(\omega)$ present the real part and the imaginary part of $H(i\omega)$, respectively. If $H(\lambda)$ is Hurwitz stable, then the zeros of the functions H_r and H_i are real, alternate, and for each ω,

$$H_i'(\omega)H_r(\omega) - H_r'(\omega)H_i(\omega) > 0. \tag{8}$$

Each of the conditions given below is sufficient for $H(\lambda)$ being Hurwitz stable:

(i) All the zeros of the functions $H_r(\omega)$ and $H_i(\omega)$ are real, alternate, and (8) holds at some ω;

(ii) All the zeros of the functions $H_r(\omega)$ are real and at each zero ω_0 (8) holds, i.e., $H_r'(\omega_0)H_i(\omega_0) < 0$;

(iii) All the zeros of the functions $H_i(\omega)$ are real and at each zero ω_0 (8) holds, i.e., $H_i'(\omega_0)H_r(\omega_0) > 0$.

In Theorem 1, checking whether all the zeros of $H_r(\omega)$ or $H_i(\omega)$ are real plays a crucial role. To ascertain such a property, one can apply the following theorem due to Pontryagin [14], [15].

Theorem 2: Let η be a real number such that the coefficient of the term of the highest degree in $H_r(\omega)$ or $H_i(\omega)$ does not vanish at $\omega = \eta$. Then, $H_r(\omega)$ or $H_i(\omega)$ has only real zeros if and only if $H_r(\omega)$ or $H_i(\omega)$ has exactly $4lM + N$ real zeros over the interval $[-2l\pi + \eta, 2l\pi + \eta]$, where l is a *sufficiently large* positive integer.

In theory, Protryagin's Theorems can serve as stability criteria for an LTI system with commensurate delays, whose characteristic function is a quasi-polynomial of retarded type or neutral type, where the coefficients are real or complex. However, they are difficult to be *numerically implemented* in practice due to the fact that there is no effective method for determining the *sufficiently large* number l. Thus, it is difficult to apply Pontryagin's Theorems to judge whether or not an LTI time-delay system is asymptotically stable. Consequently, there is no further development in the direction of Pontryagin's theorems for a long period.

Since 1969, a τ-decomposition method has been widely developed in the analysis of the location of zeros of the quasi-polynomials for LTI time-delay systems. Such a method involves first decomposing the positive time delay τ axis into many intervals over each of which the number of zeros of the quasi-polynomial in the open right-half plane never change, and then investigating the change of the number of zeros in the open right-half plane when crossing the boundary points of the intervals [16]. One can analyze the Hurwitz stability of an LTI system with fixed time delays indirectly via the τ-decomposition method. Most of the existing results in the distribution analysis of zeros of the quasi-polynomials for LTI time-delay systems in the literature are based on the τ-decomposition method, see e.g., [16]–[26], where references [16]–[19], [23], [25], [26] considered the quasi-polynomials of retarded type for LTI systems with commensurate delays, and reference [21] stressed the quasi-polynomial of neutral type for LTI systems with commensurate delays. Besides, there are other methods for the analysis of the distribution of zeros of the quasi-polynomials for LTI systems with commensurate delays. A Lambert W function based method can be applied to calculation of zeros of the characteristic function of retarded type one by one from right to left in the complex plane for the LTI systems with single delay or commensurate delays [27]. Reference [28] is devoted to the analytic study of the distribution of zeros of the quasi-polynomial with respect to the coefficient variation for a scaler retarded single delay system with either real or complex coefficients. Reference [29] describes DDE-BIFTOOL, a Matlab package for numerical bifurcation analysis of systems of delay differential equations with several fixed, discrete delays. For more information about time-delay systems, one can see references [4], [30], [31].

It should be pointed out that on the one hand, only a few studies in the literature consider the distribution of zeros of quasi-polynomials with complex coefficients. In fact, a quasi-polynomial with complex coefficients also plays an important role in applications, such as consensus of multi-agent systems with a directed network topology [32]. On the other hand, many results in the literature focus on LTI systems with *commensurate delays*, where most of the results are only valid for the quasi-polynomials of retarded type due to the messy property of the quasi-polynomials of neutral type [31]. For an LTI system with *incommensurate delays*, the analysis of the distribution of zeros of the corresponding quasi-polynomial is a challenge issue [11]. Most of the previous studies on this issue are still based on a τ-decomposition method with respect to the quasi-polynomials with real coefficients. The cluster treatment of characteristic zeros for LTI systems with two delays of retarded type or neutral type was studied in [20], [33]–[35]. Stability switching hypersurfaces of a class of LTI systems with three or multiple time delays were extracted [22]. Stability crossing sets were obtained for an LTI system of neutral type with two delays [36] and with three or multiple delays [24] in the delay parameter space.

We are now back to Pontryagin's Theorems and would like to discuss about future research. Among the existing results on the distribution of zeros of quasi-polynomials for LTI time-delay systems, Pontryagin's Theorems can be directly applied to stability judgement in theory. Furthermore, the quasi-polynomial form due to Pontryagin is probably one of the most general [16] in various methods for stability analysis of LTI time-delay systems. Besides, over the past two decades, the stability criteria by Pontryagin for quasi-polynomials play an important role in low-order stabilization of time-delay systems, see e.g., [11], [37]–[42]. Based on Pontryagin's Theorems, we proposed a new one revealing information about zeros of quasi-polynomials with real coefficients in the open right-half plane and presented some PID controllers for LTI systems with single delay via dominant eigenvalue assignment to further improve the dynamic performance in addition to stability [12]. However, due to the difficulty in *numerical implementation*, Pontyagin's Theorems have not found wide applications expect for some single delay systems [11]. It seems that it is challenging to solve the problem on the numerical implementation for Pontryagin's Theorems.

To end this perspective, we raise two open questions for future research.

i) How to derive Pontryagin-like results that can be numerically implemented for the determination of the number of zeros in the open right-half complex plane of the quasi-polynomials for LTI systems with commensurate delays?

ii) How to develop a general mathematical analysis of the distribution of zeros of the quasi-polynomials for LTI systems with incommensurate delays?

We do hope you will join us in this endeavor to discuss about this important issue with your own insight and research.

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