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## Insights in Characterizing Asymptotic Behavior for Quasipolynomials with Two Delays

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## II. PRELIMINARIES

### A. Retarded Linear Time-Invariant Systems

Consider a retarded LTI system with  $h_a$ -delays  $\tau_k$ , described in the state-space form as:

$$\dot{x}(t) = A_0 x(t) + \sum_{k=1}^2 A_k x(t - \tau_k), \quad \tau_k \geq 0, \quad (1)$$

or by the differential-difference equation

$$y^{(n)}(t) + \sum_{\ell=0}^{n-1} \sum_{k=0}^2 a_{k\ell} y^{(\ell)}(t - \tau_k) = 0, \quad \tau_k \geq 0, \quad (2)$$

with characteristic function given by the quasi-polynomial:

$$f(s, \tau) = \sum_{k=0}^h p_k(s) e^{-\tilde{\tau}_k s}, \quad \tau_k \geq 0, \quad (3)$$

where  $\tilde{\tau}_k$  is a linear combination of the delays  $\tau_j$  such that  $\tilde{\tau}_k = \sum_j c_{kj} \tau_j$ , and the polynomials  $p_k$  are given by

$$p_0(s) = s^n + \sum_{\ell=0}^{n-1} a_{0\ell} s^\ell, \quad p_k(s) = \sum_{\ell=0}^{n-1} a_{k\ell} s^\ell.$$

### B. Local Representation of Analytic Functions

Is it possible to reduce the analytic properties of  $f(x, y)$  to algebraic ones. To this purpose, let us consider the following result (for further details see [8]).

**Theorem 1 (Weierstrass Preparation Theorem):** Let  $f(z, \mathbf{x})$  be an analytic function vanishing at the singular point  $z_0 \in \mathbb{C}$ ,  $\mathbf{x}_0 \in \mathbb{C}^n$ , where  $z = z_0$  is an  $m$ -multiple root of the equation  $f(z, \mathbf{x}) = 0$ , i.e.,

$$f(z_0, \mathbf{x}_0) = \frac{\partial f}{\partial z} = \dots = \frac{\partial^{m-1} f}{\partial z^{m-1}} = 0, \quad \frac{\partial^m f}{\partial z^m} \neq 0.$$

where derivatives are evaluated at  $(z_0, \mathbf{x}_0)$ . Then, there exist a neighborhood  $U_0 \subset \mathbb{C}^{n+1}$  of the point  $(z_0, \mathbf{x}_0) \in \mathbb{C}^{n+1}$  in which the function  $f(z, \mathbf{x})$  can be expressed as

$$f(z, \mathbf{x}) = W(z, \mathbf{x}) b(z, \mathbf{x}), \quad (4)$$

where  $W(z, \mathbf{x})$  is given by

$$(z - z_0)^m + w_{m-1}(\mathbf{x})(z - z_0)^{m-1} + \dots + w_0(\mathbf{x}),$$

and  $w_0(\mathbf{x}), \dots, w_{m-1}(\mathbf{x})$ ,  $b(z, \mathbf{x})$  are analytic functions uniquely defined by the function  $f(z, \mathbf{x})$ , and  $w_i(\mathbf{x}_0) = 0$ ,  $b(z_0, \mathbf{x}_0) \neq 0$ .

**Remark 1:** The holomorphic function

$$W(z, \mathbf{x}) = z^m + w_{m-1}(\mathbf{x}) z^{m-1} + \dots + w_0(\mathbf{x}), \quad (5)$$

is known as the *Weierstrass polynomial* (for further details on Weierstrass polynomials, see, for instance, [9]).

**Remark 2:** It can be seen from Theorem 1, that since  $b(z, \mathbf{x})$  is an holomorphic non vanishing function at  $(0, \mathbf{0})$ , then, there must exist some neighborhood  $U \subset \mathbb{C}^n$  at which  $b(z, \mathbf{x})$  preserves the same property. Hence, based on this observation we can ensure that the roots behavior of a given quasi-polynomial  $f$  in the neighborhood  $U$  will be completely described by the roots behavior of  $W(\mathbf{x}, x)$ .

### C. Newton Diagram Method

It is well known that solutions of the equation  $f(x, y) = 0$  can be computed term by term by means of the *Newton Diagram Method*. Thus, in order to use such a procedure, let us introduce the following notation (for more details, see, for instance, [10]). Let  $f(x, y)$  be a *pseudo-polynomial* in  $y$ , i.e.,

$$f(x, y) = \sum_{k=0}^n a_k(x) y^k, \quad (6)$$

where the corresponding coefficients are given by,

$$a_k(x) = x^{\rho_k} \sum_{r=0}^{\infty} a_{rk} x^{r/q}, \quad (7)$$

$a_{rk} \in \mathbb{C}$ ,  $x$  and  $y$  are complex variables,  $\rho_k$  are non-negative rational numbers,  $q$  is an arbitrary natural number,  $a_n(x) \neq 0$ , and  $a_0(x) \neq 0$ .

Since by simple translation, any point on a curve can be moved to the origin, we will consider expansions of the solution of (6)  $f(x, y) = 0$  around the origin, in the following form

$$y(x) = y_{\epsilon_1} x^{\epsilon_1} + y_{\epsilon_2} x^{\epsilon_2} + y_{\epsilon_3} x^{\epsilon_3} + \dots, \quad (8)$$

where  $\epsilon_1 < \epsilon_2 < \epsilon_3 < \dots$  and  $y_{\epsilon_1} \neq 0$ . To determine the possible values of  $\epsilon_1, y_{\epsilon_1}, \epsilon_2, y_{\epsilon_2}, \dots$ , it is necessary to consider the *Newton's diagram*.

**Definition 2.1 (Newton's Diagram and Polygon):** Given a pseudo-polynomial of the form (6) with coefficients given by (7), plot  $k$  versus  $\rho_k$  for  $k = 0, 1, \dots, n$  (if  $a_k(\cdot) \equiv 0$ , the corresponding point is disregarded). Denote each of these points by  $\pi_k = (k, \rho_k)$  and let

$$\Pi = \{\pi_k : a_k(\cdot) \neq 0\},$$

be the set of all plotted points. Then, the set  $\Pi$  will be called the *Newton diagram*, and the *Newton polygon* associated with  $f(x, y)$  will be given by the lower boundary of the convex hull of the set  $\Pi$ .

For a given  $f(x, y)$ , Fig.1 simply illustrates Definition 2.1. Thus, the leading term of the solutions have exponents given

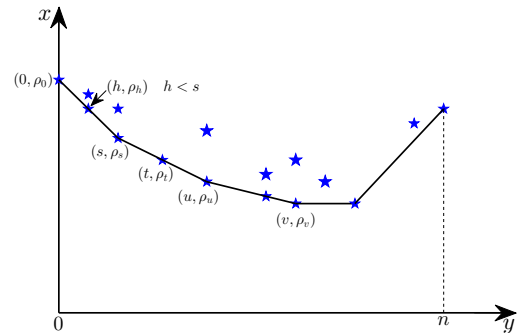


Fig. 1. The Newton Diagram for  $f(x, y)$ .

by the slopes  $\gamma$  by making  $\epsilon = \gamma$ . The coefficients are given by the non-zero solutions of the polynomial equation

$$\mathcal{P}(y_\epsilon) := \sum_i a_{0,i} y_\epsilon^i = 0, \quad (9)$$

where the sum runs over the terms satisfying  $\rho_k + \gamma k = \nu$  with constant  $\nu \in \mathbb{Q}$ . For equations  $f(x, y) = 0$ , the *Newton Diagram Method* can be formalized by the following theorem ( see [11]).

**Theorem 2 (Puiseux Theorem):** The equation  $f(x, y) = 0$ , with  $f$  given in formal power series such that  $f(0, 0) = 0$ , posses at least one solution in power series of the form:

$$x = t^q, \quad y = \sum_{i=1}^{\infty} c_i t^i, \quad q \in \mathbb{N}.$$

#### D. Generalized Puiseux Series and Cones

Theorem 2 allows to find fractional power series solutions, known as Puiseux series, in the case of multiparameter algebraic equations. In this vein, when we deal with singularities of greater dimension, we must use a ring of multi-variable fractional power series. In [12] the author defines fractional power series ring that contains the solutions of algebraic hyper-surfaces. This can be achieved through formal power series defined in a geometric way, by taking infinite power series

$$\sum_{i=1}^{\infty} c_{\mathbf{a}_i} \mathbf{x}^{\mathbf{a}_i/d}, \quad \text{where } \mathbf{x}^{\mathbf{a}} = x_1^{\mathbf{a}_1} \cdots x_n^{\mathbf{a}_n},$$

where the exponents  $\mathbf{a}$  are taken from a fixed convex cones with structure related to its Newton polytopes [13].

**Definition 2.2:** A convex polyhedral cone is a set of the form

$$\sigma = \left\{ \sum_{i=1}^m \lambda_i v_i : \lambda_i \in \mathbb{R}_+ \right\},$$

where  $M = \{v_1, \dots, v_m\}$  is a finite set of vectors in  $\mathbb{R}^n$ .

We will use fractional iterated power series of several variables as *Generalized Puiseux Power Series* (see [14], [15]), denoted by  $K_{\mathbf{x},d}$ . This series can be constructed by induction, taking as a bases the univariate case  $K_{x_1,d}$  and then, proceed with the field of power series in  $x_1^{1/d}$  with power series coefficients in  $x_2^{1/d} \cdots x_n^{1/d}$  such that

$$K_{\mathbf{x},d} = \mathbb{C} \left( \left( x_1^{1/d} \right) \right) \cdots \left( \left( x_n^{1/d} \right) \right).$$

#### E. Motivating Examples

Even though we can reduce the analysis of a given entire function  $f$  to the study of an algebraic function  $P_f$ , in this section we aim to pointing out some difficulties that arise in regarding multiparameter functions. In order to illustrate such arguments, let us consider the following motivating example.

**Example 2.1:** Consider the following polynomial

$$P(z, \epsilon_1, \epsilon_2) = z^2 + 3\epsilon_1 z + 2(\epsilon_1^2 + 2\epsilon_2^2), \quad (10)$$

where  $\epsilon_1$  and  $\epsilon_2$  are considered as perturbation parameters. It is clear to see, that for  $\epsilon_1 = \epsilon_2 = 0$ ,  $z = 0$  is a root of multiplicity two.

In this case, the solutions  $z_{1,2}(\epsilon)$  are not analytic at  $\epsilon := (\epsilon_1, \epsilon_2) = (0, 0) = \mathbf{0}$ . Furthermore,  $z_{1,2}(\epsilon)$  does not have a *unique* representation as a power series which is convergent in some punctured neighborhood of the origin. In order to

illustrate this assertion, let us consider the region  $|\epsilon_1| < |\epsilon_2|$ , in this region the solutions admit the following representation

$$z_{1,2}(\epsilon) = -\frac{1}{2}(3\epsilon_1 \pm i4\epsilon_2) + \frac{1}{16}\epsilon_1 \left( \pm i \frac{\epsilon_1}{\epsilon_2} \pm \frac{i}{64} \left( \frac{\epsilon_1}{\epsilon_2} \right)^3 \pm \frac{i}{2048} \left( \frac{\epsilon_1}{\epsilon_2} \right)^5 + \mathcal{O} \left( \left( \frac{\epsilon_1}{\epsilon_2} \right)^5 \right) \right).$$

Now, if instead of the previous region, we consider the region  $|\epsilon_2| < |\epsilon_1|$ , then for  $k \in \{1, 2\}$  the solutions admit the following representation

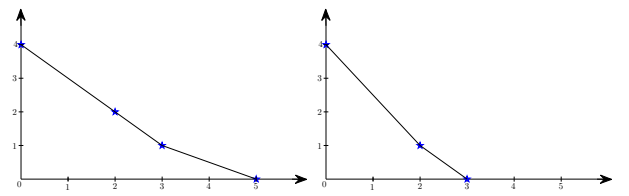
$$z_k(\epsilon) = -2^{k-1}\epsilon_1 + (-1)^k 4\epsilon_2 \left( \frac{\epsilon_2}{\epsilon_1} + 4 \left( \frac{\epsilon_2}{\epsilon_1} \right)^3 + 32 \left( \frac{\epsilon_2}{\epsilon_1} \right)^5 + \mathcal{O} \left( \left( \frac{\epsilon_2}{\epsilon_1} \right)^5 \right) \right).$$

The above arguments clearly have shown that some further considerations must be taken into account in the case of multiparameter functions. Next, as mentioned in previous sections, in the single parameter case, the Newton diagram is a powerful tool to analyze the asymptotic behavior for the solutions of pseudo-polynomials. However, in order to be able to apply such a procedure to the multiparameter case, some special situations must be taken into consideration. In order to motivate the above arguments, let us consider the following.

**Example 2.2:** Consider the polynomial

$$P(z, \epsilon) := z^5 + (\epsilon_1 \epsilon_2^3 + \epsilon_1^2 \epsilon_2^2) z^3 + (\epsilon_1^2 \epsilon_2^2 + \epsilon_1^3 \epsilon_2) z^2 + (\epsilon_1^4 \epsilon_2). \quad (11)$$

Clearly,  $z = 0$  is a 5-multiple root at  $\epsilon = (0, 0)$ . Now, let us form the Newton diagram with respect to  $\epsilon_1$ , obtaining  $\Pi = \{(0, 4), (2, 2), (3, 1), (5, 0)\}$ , illustrated in Fig.2-(a). The slope  $\beta_0 = 1$  determines 3-solutions with respect to



(a) Newton polygon with respect to  $\epsilon_1$ . (b) Newton polygon with respect to  $\epsilon_2$ .

Fig. 2. Newton polygons for  $P(z, \epsilon)$  in Example 11.

$\epsilon_1$ , and coefficients that are solutions of the polynomial

$$\mathcal{P}(\xi) = \epsilon_2 + \epsilon_2^2 \xi^2 + \epsilon_2^3 \xi^3 = 0.$$

In this case, it is clear that the solutions cannot be easily computed. In order to compute solutions by applying the Newton procedure, we seek for a monic polynomial. Thus, with the aim of overcoming such difficulty, let us consider the change of variables (blowing-ups)

$$\zeta := \xi \quad \epsilon_1 = v_1 \epsilon_2 \quad \epsilon_2 = v_2,$$

and

$$v_1 = y_1 v_2 \quad v_2 = y_2.$$

These change of variables enable us to avoid horizontal segments in the subsequent steps of the process. The resulting

polynomial  $P'(y_1, y_2)$  posses the same Newton polygon, and the segment with  $\beta_0 = 1$  has a monic polynomial

$$y_2^{-5} \mathcal{P}'(\xi, y_2) = y_2^4 + y_2 \xi^2 + \xi^3 = 0.$$

Applying Newton procedure, (see figure 2-(b)) to the above equation, we derive the fractional power series solution of  $P'$ :

$$\begin{aligned} \zeta_1(y_1, y_2) &= -y_2 y_1 + o(y_1 y_2), \\ \zeta_{2,3}(y_1, y_2) &= \pm i y_2^{2/3} y_1 + o\left(y_1 y_2^{1/3}\right). \end{aligned}$$

### F. Problem Formulation

The present work is focused on computing the first approximation of the solution of quasi-polynomials around multiple imaginary roots. In this vein, we will focus in the following problems:

- (i) compute an approximation of the associated Weierstrass polynomial;
- (ii) extend the Newton diagram procedure to Weierstrass polynomial of several variables;
- (iii) obtain conditions that allow obtaining Puiseux series solutions

$$s(\tau_1, \tau_2) = c(\tau_2^{1/d}) \tau_1^\beta + o(\tau_1^{1/d} \tau_2^{1/d}),$$

where  $\beta = \alpha/d$  and  $\alpha \in \mathbb{N}$ ;

- (iv) give conditions on  $f(s, \tau)$  which describes the splitting properties of its solutions  $s(\tau_1, \tau_2)$ : Regular Splitting, Completely Regular Splitting and Non Regular Splitting.

## III. MAIN RESULTS

### A. Computation of Weierstrass Polynomial

In [8], the authors propose a method to compute the Weierstrass polynomial for an holomorphic function. This method is based on its partial derivatives and combinatorial factors related in a recursive way. For the case of holomorphic function,  $f(z, \mathbf{x})$  of complex variables with  $\mathbf{x} = (x_1, x_2)$  and  $z = 0$  a  $m$ -multiple root at  $(x_1, x_2) = (0, 0)$  the computation is given as follows. The coefficients  $w_i$  (5) are analytic,  $w_i(0, 0) = 0$  and can expressed as convergent power series:

$$w_i(x_1, x_2) = \sum_{h_1+h_2=1}^{\infty} \frac{1}{h_1! h_2!} w_{i, \mathbf{h}} x_1^{h_1} x_2^{h_2},$$

where  $\mathbf{h} = (h_1, h_2)$ . It is not difficult to see that the coefficients  $w_{i, \mathbf{h}}$  can be compute by means of the following partial derivatives

$$w_{i, \mathbf{h}} = \left. \frac{\partial^{h_1+h_2} w_i}{\partial x_2^{h_1} \partial x_1^{h_2}} \right|_{(0,0)}.$$

Since the analytic function locally satisfy  $f = Wb$ , thus its partial derivatives satisfy the following recursive relations

$$w_{i, \mathbf{h}} = \sum_{j=0}^i \alpha_{ij} F_{j, \mathbf{h}}, \quad (12)$$

$$F_{j, \mathbf{h}} = f_{j, \mathbf{h}} - \sum_{k=0}^j \sum_{\mathbf{h}'+\mathbf{h}''=\mathbf{h}} c(j, k; \mathbf{h}', \mathbf{h}'') w_{k, \mathbf{h}'} b_{j-k, \mathbf{h}''},$$

with  $\mathbf{h}' \neq \mathbf{0}$ ,  $\mathbf{h}'' \neq \mathbf{0}$  and constant coefficients:

$$\alpha_{jj} = \frac{m!}{j! f_{m, \mathbf{0}}}, \quad \alpha_{ij} = -\frac{m!}{f_{m, \mathbf{0}}} \sum_{k=j}^{i-1} \frac{f_{m+i-k, \mathbf{0}} \alpha_{kj}}{(m+i-k)!},$$

$$c(j, k; \mathbf{h}_1, \mathbf{h}_2) = \frac{j!}{(j-k)!} \prod_{s=1}^2 \frac{(h'_s + h''_s)!}{h'_s! h''_s!},$$

and for  $\mathbf{h}' \neq \mathbf{0}$ ,  $k' = k + m$ ,  $b_{k, \mathbf{h}}$  is given by

$$\frac{k!}{(m+k)!} \left[ f_{k', \mathbf{h}} - \sum_{j=0}^{m-1} \sum_{\mathbf{h}'+\mathbf{h}''=\mathbf{h}} c(k', j; \mathbf{h}', \mathbf{h}'') w_{j, \mathbf{h}'} b_{k'-j, \mathbf{h}''} \right].$$

Since we are only interested in the leading terms of  $w_i$ , namely a first approximation of the Weierstrass polynomial, we adopt the following notation.

*Definition 3.1:* Let the natural numbers  $n_i^{(j)}$ , for  $i \in \{0, 1, \dots, m-1\}$  and  $j = 1, 2$ , denote the first non zero partial derivative in  $(z, x_1, x_2)$  of  $f$ , such that the following conditions hold

$$f(0, 0, 0) = \frac{\partial^i f}{\partial z^i} = \dots = \frac{\partial^{i+n_i^{(j)}-1} f}{\partial z^i \partial \tau_j^{n_i^{(j)}-1}} = 0, \quad \frac{\partial^{i+n_i^{(j)}} f}{\partial z^i \partial \tau_j^{n_i^{(j)}}} \neq 0,$$

with derivatives evaluated at  $(0, 0, 0)$ . For  $n_i^{(j)} = \infty$  we have derivatives

$$f_{i, (0,0)} = \dots = f_{i, (0, n_i^{(j)}-1)} = 0, \quad f_{i, (0, n_i^{(j)})} \neq 0,$$

evaluated at  $(z, \mathbf{x}) = (0, 0, 1)$ , with  $n_i^{(j)} \in \mathbb{Z}_{\geq 0}$ .

Leading terms of coefficients  $w_i$  can be easy found up to the  $n_i^{(j)}$  and  $n_i^{(j)}$  derivatives, as a first observation we give the following result.

*Proposition 1:* Suppose that the Weierstrass polynomial has first non-zero partial derivative, such that

$$n_i^{(j)} > n_{i+1}^{(j)}, \quad 0 \leq i < m \text{ and } j = 1, 2.$$

Then, the leading terms of  $w_i(\mathbf{x})$  are given by

$$w_i(x_1, x_2) = \alpha_{i,i} f_{i, (n_i^{(1)}, 0)} x_1^{n_i^{(1)}} + \alpha_{i,i} f_{i, (0, n_i^{(2)})} x_2^{n_i^{(2)}} + \dots$$

If  $n_i^{(j)} = \infty$  we get

$$w_i(x_1, x_2) = \alpha_{i,i} f_{i, (n_i^{(j)}, \eta)} x_1^{n_i^{(j)}} x_2^\eta + \dots$$

*Remark 3:* There may be a case in which

$$f_{i, (h_1, h_2)} \Big|_{(0,0,0)} = 0 \quad \forall h_1, h_2 \in \mathbb{N},$$

since  $w_i$  are analytic functions, this is equivalent to  $w_i(\mathbf{x}) \equiv 0$  for  $i \leq i \leq \kappa - 1$ . Thus, according to Theorem 1  $f$  has the following local structure:

$$z^\kappa [z^{m-\kappa} + w_{m-\kappa}(\mathbf{x}) z^{m-\kappa-1} + \dots + w_\kappa(\mathbf{x})] b(z, \mathbf{x}).$$

Thus, there are  $\kappa$ -invariant solutions  $z = 0$  for all  $\mathbf{x}$ . If such number  $\kappa$  does not exist (i.e., if such situation does not occur), then  $\kappa$  will be simply defined as  $\kappa := 0$ .

### B. The Newton Diagram Method for Two Parameters

Consider the monic pseudo-polynomial  $f(z, \mathbf{x})$  of the form

$$z^m + a_{m-1}(x_1, x_2)z^{m-1} + \dots + a_0(x_1, x_2), \quad (13)$$

with  $a_i(\mathbf{x}) \in \mathbb{C}[[\mathbf{x}]]$ , such that  $f(0, \mathbf{0}) = 0$ . The equation  $f = 0$  can be solved by applying the Newton diagram method, this is done taking into account just one variable, say  $x_1$ , and proceeding iteratively. We take the point  $\pi_k$  as the order of  $a_k$  in  $x_1$ , taking  $x_2$  as an element of  $\mathbb{C}((x_2))$ . For such a purpose, the following definition will be useful

$$\rho_k := \text{ord}_{x_1}(a_k(x_1, x_2)) = \text{ord}(a_k(x_1, 1)). \quad (14)$$

Then, the *Newton Polygon* of  $f(z, \mathbf{x})$ , with respect to  $x_1$ , is defined by the lower boundary of the convex hull of the points  $(k, \rho_k) \in \Pi$  (see, Definition 2.1). In order to apply the the Newton diagram procedure, according to Section II-D, the solution  $z$  will take the following structure

$$z(x_1, x_2) = \sum_i c_i(x_2)x_1^{i/d},$$

where the coefficient  $c_i(x_2)$ , is in general, given by an univariate Puiseux series in  $x_2$ .

1) *First Step into the Newton Procedure*: Let us suppose that we have determined the Newton diagram of the Weierstrass polynomial (13) of  $f$ . Since we are dealing with a monic polynomials, the Newton polygon has a finite number of segments, each one with a corresponding set of points  $\Pi^{(\ell)}$  and rational numbers  $\beta_\ell \geq 0$  satisfying

$$\beta_0 > \beta_1 > \dots > \beta_r.$$

Therefore, the segments are presented in two possible ways. The first one, a Newton polygon with an horizontal segment determined by  $\beta_r = 0$  and the second one, where  $\beta_r > 0$ . In this vein, for  $0 \leq \kappa < m$ , the Newton Diagram  $\Pi$  is given as the set  $\Pi = \Pi' \cup \Pi''$

$$\{(0, \rho_0), \dots, (\kappa, 0)\} \cup \{(\kappa, 0), \dots, (\ell, \rho_\ell), \dots, (m, 0)\}.$$

Lets take at the first step of the process a horizontal segment with slope  $\beta_r = 0$ .

*Proposition 2*: Let  $f(z, \mathbf{x})$  be a pseudo-polynomial with the same structure as (13). Suppose that at least one coefficient  $a_i(\mathbf{x})$  posses order  $\rho_i = 0$ . Then, the equation  $\mathcal{P}(x_1, \xi) = 0$  (9) of the corresponding horizontal segment has solutions  $c_k(x_2^{1/d})$  in the form of Puiseux series.

Now, at the first step of the process, the case with negative slope is considered.

*Proposition 3*: Assume that  $f$  has the same structure than (13) and assume that the first Newton diagram posses a segment with negative slope. Then, there exist a change of variables  $(z, x_1, x_2) \mapsto (\zeta, y_1, y_2)$  such that the polynomial  $\mathcal{P}(y_2, \xi)$  has Puiseux series solutions  $c_k(y_2^{1/d})$ .

Hence, applying to  $f$  the change of variables  $z = \zeta$ ,  $x_1 = y_1^{a_1}$  and  $x_2 = y_2^{a_2}$  we get  $f(\zeta, y_1, y_2)$ , which can be solved. Therefore, solutions  $z(x_1, x_2)$  of  $f = 0$  are obtained by applying the inverse change of variables to solutions  $\zeta$ .

The following theorem allow us to use the iterative Newton procedure described above.

*Theorem 3* (See [14].): The iteration of the classical Newton Procedure for one variable gives rise to representation of all the roots of the equation (13) by generalized Puiseux series with terms  $\mathbf{x}^{\mathbf{a}/d}$ ,  $d \in \mathbb{Z}_+$ , such that  $\mathbf{a}$  belong to  $n$ -dimensional, lex-positive strictly convex polyhedral cone.

### C. Newton Polygon Algorithm

Let us consider the points  $\pi_\ell = (\ell, \rho_\ell) \in \Pi$  to get the Newton polygon, obtaining a finite number of segments with slopes  $-\beta_r$ . Now, taking as a basis the Newton procedure introduced in Section II-C, we propose the Algorithm 1. In

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#### Algorithm 1 Auxiliary Puiseux Series Expansion

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Let  $f(s, \tau)$  have a critical pair such that  $s^* = i\omega^*$  is a  $m$ -multiple root at  $\tau = (\tau_1^*, \tau_2^*)$ . Consider the initial values as  $r := 0$ ,  $i_{-1} := \kappa$ ,  $j := \kappa$  and  $k := \rho_\kappa$ .

- 1) Set  $\mathcal{E}_r := \left\{ \frac{\ell-k}{j-i} : (i, \ell) \in \Pi, \text{ and } i > j \right\}$ ;
  - 2) Let  $\beta_r := \max \mathcal{E}_j$  and  $\Pi^{(r)} := \left\{ (i, \ell) \in \Pi : \beta_j \equiv \frac{k-\ell}{j-i} \right\}$ ;
  - 3) Set  $(i_r, \ell_r) \in \Pi^{(r)}$  such that  $i_r \geq i$ ,  $\forall (i, \ell) \in \Pi^{(r)}$ ;
  - 4) Set  $j := i_r$ ,  $m_r := i_r - i_{r-1}$  and  $r = r + 1$ ;
  - 5) If  $j < m$  go to step 1. Otherwise the algorithm ends.
- 

the algorithm 1,  $\kappa$  is defined according to Remark 3. In order to used the iterated Newton diagram procedure we need to find solutions of the equation  $\mathcal{P}$ , which can be solved by the usual Newton diagram method. For this purpose the input  $\Pi$  of algorithm, has points  $\pi_\ell$  determined by equation  $\mathcal{P} = 0$ .

### D. Puiseux Series for Quasi-Polynomials with two delays

Since any critical solution  $(s^*, \tau_1^*, \tau_2^*)$  can always be translated to the origin by appropriate shifts  $s \mapsto s - s^*$ ,  $\tau_1 \mapsto \tau_1 - \tau_1^*$ ,  $\tau_2 \mapsto \tau_2 - \tau_2^*$ , hereinafter we will assume that  $(s^*, \tau_1^*, \tau_2^*) = (0, 0, 0)$ .

*Proposition 4*: Consider the following quasi-polynomial

$$f(s, \tau_1, \tau_2) = p_0(s) + p_1(s)e^{-s\tau_1} + p_2(s)e^{-s\tau_2}, \quad (15)$$

with  $s = 0$  a  $m$ -multiple root at  $\tau = (0, 0)$  and local representation  $f(s, \tau) = W(\tau)b(s, \tau)$ . If  $n_i^{(j)} = 0$  for  $i = 0, 1, \dots, k$  then, the  $k+1$  coefficients of the Weierstrass polynomial  $W$  satisfy

$$w_{m-i}(\tau) \equiv 0, \quad i \in \{0, 1, \dots, k\}.$$

*Proposition 5*: Let quasi-polynomial  $f(s, \tau)$  have a  $m$ -multiple roots  $s = 0$  at  $\tau = (0, 0)$ , with associated Weierstrass polynomial  $W$ . Assume that

$$\mathcal{R} \left( W, \frac{\partial W}{\partial s} \right) = \tau_1^{a_1} \tau_2^{a_2} \mathcal{U}(\tau_1, \tau_2) \quad \text{such that } \mathcal{U}(0, 0) \neq 0,$$

where  $(a_1, a_2) \in \mathbb{Z}_{\geq 0}^2 \setminus \{\mathbf{0}\}$ ,  $\mathcal{U} \in \mathbb{C}\{\tau_1, \tau_2\}$ . Then,  $f = 0$  posses  $m$  solutions given by a generalized Puiseux series. The following result gives conditions to have a regular Newton diagram.

*Proposition 6*: Let  $W(s, \tau_1, \tau_2)$  be the Weierstrass polynomial of a given quasi-polynomial  $f(s, \tau_1, \tau_2)$ . Assume

that for a given  $\ell$ -segment of the Newton diagram, be  $-\beta_\ell < 0$  its slope with corresponding points  $\Pi^{(\ell)} = \{(k_1, \rho_{k_1}), (k_2, \rho_{k_2}), \dots, (k_s, \rho_{k_s})\}$ . Then, the equation  $\mathcal{P}$  can be solved without any change of variables if the leading terms of the coefficients  $w_{k_i}$  satisfy

$$w_{k_i, (\rho_{k_i}, \eta_{k_i})} \neq 0 \text{ whenever } \eta_{k_i} > \eta_{k_s}, \quad i < s.$$

Finally, using iterated Newton diagram procedure together with the Weierstrass polynomial of the quasi-polynomial  $f(s, \tau)$ , we can find the leading terms of the power series solutions.

*Proposition 7:* Let  $s^* = i\omega^*$  be a  $m$ -multiple root of  $f(s, \tau)$  at  $\tau^* = (\tau_1^*, \tau_2^*)$ . Assume that  $\kappa = 0$  and  $r, \beta_j, (i_j, \ell_j), m_j$  and  $\Pi^{(j)}$ , for  $j = 0, 1, \dots, r-1$  are given by Algorithm 1. Then, at  $\tau = \tau^*$  the  $m$ -zeros of  $f(s, \tau)$  can be expanded as

$$s_{j\sigma}(\tau) = i\omega^* + c_{j\sigma}(\tau_2) (\tau_1 - \tau_1^*)^{\beta_j} + o\left(|\tau_1 - \tau_1^*|^{\beta_j} |\tau_2 - \tau_2^*|^{\beta'_j}\right),$$

for  $j = 0, 1, \dots, r-1, \sigma = 0, \dots, m_j$  and  $m = m_0 + \dots + m_{r-1}$ . For  $\beta_j > 0$  the coefficients  $c_{j\sigma}(x_2)$  are roots of the polynomial:

$$\mathcal{P}_j(\xi, x_2) = \sum_{k=i_{j-1}}^{i_j} w_{k, (n_k^{(1)}, n'_k)} \tau_2^{n'_k} \xi^{k-i_{j-1}}, \quad (k, n_k^{(1)}) \in \Pi^{(j)},$$

when  $\beta_{r-1} = 0$ , the coefficients are given by the solution of

$$\mathcal{P}_j(\xi, x_2) = \sum_{k=i_{j-1}}^{i_j} w_{k, (0, n_k^{(2)})} \tau_2^{n_k^{(2)}} \xi^{k-i_{j-1}}, \quad (k, 0) \in \Pi^{(r-1)}$$

where  $n_k^{(1)}, n_k^{(2)}, n'_k$  are given by the first non-zero partial derivatives of Definition 3.1; the constant terms  $w_{k, (n, \eta)} \in \mathbb{C}$  are computed using (12).

### E. Splitting Properties

The main goal of this subsection is to explore some qualitative properties of the solutions  $s(\tau_1, \tau_2)$  of the quasi-polynomial  $f$  around the  $m$ -multiple critical pair  $(0, \mathbf{0})$ . The solution curve  $\mathcal{C} \in \mathbb{C}^3$ , defined by the equation  $f = 0$ , is composed of  $m$  generalized Puiseux series solutions. These solutions can be arranged in  $r$ -branches, given in the following form

$$s_{j\sigma}(\tau) = c_{j\sigma} \tau_1^{\beta_j} \tau_2^{\beta'_j} + o\left(|\tau_1|^{\beta_j} |\tau_2|^{\beta'_j}\right), \quad (16)$$

with  $\sigma = 0, \dots, m'_j - 1$  and  $j = 0, \dots, r-1$ . The leading term has exponents defined by  $\beta_j = p/m_j, \beta'_j = q/m'_j$ , with  $p, q \in \mathbb{Z}_{\geq 0}$ . Each branch has multiplicity  $m_j = m'_0 + m'_1 + \dots + m'_\ell$ , for some  $\ell \in \mathbb{Z}_{\geq 0}$  such that  $m = m_0 + m_1 + \dots + m_{r-1}$ . In this vein, we have the following definition.

*Definition 3.2:* We say that there is a *Completely Regular Splitting* (CRS) property of the solution  $s^* = 0$  at  $\tau^* = \mathbf{0}$  if  $c_{j\sigma} \neq 0$ , and  $p \cdot q \leq 1, \forall j$ . For the *Regular Splitting* (RS) property, some of the coefficients  $c_{j\sigma}$  for which  $m_j = 1$  may be equal to zero. In the remaining cases of the coefficient  $c_{j\sigma}$  we say that *Non Regular Splitting* (NRS) property is present.

In this view, we have the following proposition.

*Proposition 8:* Let  $f(s; \tau)$  be a quasi-polynomial with  $s^* = i\omega$  a  $m$ -multiple root at  $(\tau_1, \tau_2) = (\tau_1^*, \tau_2^*)$  such that satisfy Proposition 5. Suppose that  $\beta_j, m_j$ , for  $j = 0, 1, \dots, r-1$  are given by Algorithm 1. Then, the following relations holds:

- 1) if  $(m_j \cdot \beta_j) \cdot (m'_j \cdot \beta'_j) \leq 1 \forall j \in \{0, 1, \dots, r-1\}$ , then the solution  $(i\omega, \tau^*)$  has the CRS property;
- 2) if the pairs  $(m_k, \beta_k)$  that do not fulfill 1), satisfy  $\beta_k \geq m_k \equiv 1$ , then the solution  $(i\omega, \tau^*)$  has the RS property;
- 3) for the remaining cases of  $\beta_j$ , the solution  $(i\omega, \tau^*)$  has the NRS property.

*Remark 4:* It should be mentioned that the Definition 3.2 takes into account the behavior of  $m - \kappa$  solutions, without considering  $\kappa$  invariant solutions.

## IV. NUMERICAL EXAMPLES

In order to illustrate the proposed approach, let us consider the following numerical examples.

*Example 4.1:* Consider the following quasi-polynomial

$$f(s, \tau) = (s^2 - 2s + 1) - 2e^{-s\tau_1} + 2\pi s e^{-s\tau_2} + e^{-2s\tau_2}, \quad (17)$$

with  $\tau = (1, \pi)$ , we have a triple root at  $s = 0$ . In order to apply the proposed results, let us consider  $\tilde{f}(s, \tau) := f(s, \tau_1 + 1, \tau_2 + \pi)$ . Now, according to the Weierstrass Preparation Theorem, the local behavior around the solution  $\mathbf{0}$  of  $\tilde{f}$  is captured by the solutions of

$$W(s, \tau) = s^3 + w_2(\tau) s^2 + w_1(\tau) s + w_0(\tau).$$

Considering Definition 3.1, we take the first partial derivatives of  $\tilde{f}$ . We have that  $n_0^{(1)} = n_0^{(2)} = \infty$ , for  $h_1 = (1, 0), h_2 = (0, 1)$  we get the natural numbers  $n_1^{(j)}$  determined by

$$f_{1, h_j} = (-1)^{j+1} 2 \Rightarrow n_1^{(j)} = 1, \quad j = 1, 2.$$

Similarly, for  $n_2^{(j)}$  we have that

$$f_{2, h_1} = -4, \quad f_{2, h_2} = 4\pi \Rightarrow n_2^{(j)} = 1.$$

Applying Proposition 4 we have that  $w_0 \equiv 0$ . Proposition 1 allows to find the leading terms given by

$$w_1(\tau) = \frac{6}{1 - \pi^3} \tau_1 - \frac{6}{1 - \pi^3} \tau_2 + \dots$$

$$w_2(\tau) = \frac{-3(3 + 4\pi^3(\pi - 1))}{2(\pi^3 - 1)^2} \tau_1 + \frac{3(4\pi - 1)}{2(\pi^3 - 1)} \tau_2 + \dots$$

Next, according to (14), the order with respect to  $\tau_1$  of  $w_i(\tau)$  define the set of points  $\Pi'' = \{(1, 0), (2, 0), (3, 0)\}$ . Hence, applying Algorithm 1, we derive the results summarized in Table I. From Table I we can observe that the Newton polygon has an horizontal slope with  $\beta_0 = 0$ . Thus, by considering Proposition 7, we need solve the polynomial equation

$$\mathcal{P}_0(\xi, \tau_2) := \xi^2 + w_{2, (0, 1)} \tau_2 \xi + w_{1, (0, 1)} \tau_2 = 0,$$

TABLE I  
RESULTS SUMMARY FOR THE QUASI-POLYNOMIAL 17.

Initial Data	Algorithm Output
$m = 3, \kappa = 1, \rho_1 = 0$	$r = 1, m_0 = 2, \beta_0 = 0$
$\Pi = \{(1, 0), (2, 0), (3, 0)\}$	$\Pi^{(0)} = \{(1, 0), (2, 0), (3, 0)\}$

TABLE II  
RESULTS SUMMARY FOR THE QUASI-POLYNOMIAL 17.

Initial Data	Algorithm Output	$\mathcal{Z} := \{z \in \mathbb{C} : \mathcal{P}_j(z) = 0\}$
$m' = 2, \kappa = 0, \rho_0 = 1$	$r = 1, m'_0 = 2, \beta'_0 = 1/2$	$\mathcal{P}_0(z) := z^2 + \frac{6}{1-\pi^3}$
$\Pi = \{(0, 1), (1, 1), (2, 0)\}$	$\Pi^{(0)} = \{(0, 1), (2, 0)\}$	$\{c_{0,\sigma} = \pm \sqrt{\frac{6}{1-\pi^3}}\}$

and by Proposition 6 we know that there is no need of change of variables. Taking as input  $\Pi = \{(0, 1), (1, 1), (2, 0)\}$ , we obtain Table II from the Newton polygon algorithm. Since  $\kappa = 1$ , there is an invariant root at  $s = 0$ . The leading terms of solutions are given by

$$s_{0,\sigma}(\tau) = \pm \sqrt{\frac{6}{1-\pi^3}} (\tau_2 - \pi)^{1/2} + o\left(|\tau_1 - 1|^{\frac{1}{2}} |\tau_2 - \pi|^{\frac{1}{2}}\right).$$

where  $\sigma \in \{0, 1\}$ . We can see that the solutions  $(0, 1, \pi)$  splits in one invariant roots  $s_0$  and two solutions such that  $\beta_0 \cdot m_1 = 1$ , thus by Proposition 8, we know that the solution possess the CRS property.

*Example 4.2:* Lets consider the quasi-polynomial  $f(s, \tau) = p_0(s) + p_1(s)e^{-s\tau_1} + p_2(s)e^{-s\tau_2}$  where

$$p_0(s) = s^5 + s^4 + \frac{4+\pi}{2}s^3 + 2s^2 + \frac{2+\pi}{2}s + 2, \quad (18a)$$

$$p_1(s) = 1, \quad p_2(s) = 2s^4 + 4s^2 + 2. \quad (18b)$$

For  $(\tau_1, \tau_2) = (\pi, 1)$ ,  $f$  has a double root at  $s = i$ . With the aim of applying the proposed methodology, let us shift from  $(i, \pi, 1)$  to the origin, obtaining  $\tilde{f}$ . We find that the first non-zero partial derivatives of the quasi-polynomial at  $(0, 0, 0)$  are given by

$$f_{0,(1,0)} = i \quad \Rightarrow n_0^{(1)} = 1, \quad f_{0,(0,n)} = 0 \Rightarrow n_0^{(2)} = \infty,$$

$$f_{1,(1,0)} = 1 - i\pi \Rightarrow n_1^{(1)} = 1, \quad f_{1,(0,n)} = 0 \Rightarrow n_1^{(2)} = \infty.$$

Hence, by Proposition 1, we have that  $\rho_j = n_j^{(1)}$  for  $j = 1, 2$ . The Newton diagram is given by  $\Pi = \{(0, 1), (1, 1), (2, 0)\}$ . Table III summarizes the results deriving from Algorithm 1. Since coefficient  $w_1$  is not over the Newton polygon, following Proposition 1, we compute the leading term of  $w_i(\tau)$ , as

$$w_0(\tau) = \frac{-2i}{(8 + \pi^2) + i(8 - 3\pi) + 16e^{-i}\tau_1} + \dots$$

From the algorithm output, we get a segment with negative

TABLE III  
RESULTS SUMMARY FOR THE QUASI-POLYNOMIAL 18.

Initial Data	Algorithm Output	$\mathcal{Z} := \{z \in \mathbb{C} : \mathcal{P}_j(z) = 0\}$
$m = 2, \kappa = 0, \rho_0 = 1$	$r = 1, m_0 = 2, \beta_0 = 1/2$	$\mathcal{P}_0(z) := z^2 + w_{0,(1,0)}$
$\Pi = \{(0, 1), (1, 1), (2, 0)\}$	$\Pi^{(0)} = \{(0, 1), (2, 0)\}$	$\{c_{0,\sigma} = \pm \sqrt{w_{0,(1,0)}}\}$

slope  $\beta_0 = 1/2$ . According to Proposition 7 we need to solve:

$$\mathcal{P}(\xi) = \xi^2 - \frac{2i}{(8 + \pi^2) + i(8 - 3\pi) + 16e^{-i}} = 0,$$

for  $\sigma \in \{0, 1\}$ , the solutions are given by

$$s_{0,\sigma}(\tau) = i \pm \frac{\sqrt{2}i^{3/2}}{\sqrt{(8 + \pi^2) + i(8 - 3\pi) + 16e^{-i}}} (\tau_1 - \pi)^{1/2} + o\left(|\tau_1 - \pi|^{\frac{1}{2}} |\tau_2 - 1|^{\frac{1}{2}}\right).$$

Since  $\beta_0 \cdot m_0 = 1$ , Proposition 8 implies that the solution  $(i, \pi, 1)$  has the CRS property. This behavior is illustrated in Figure 3.

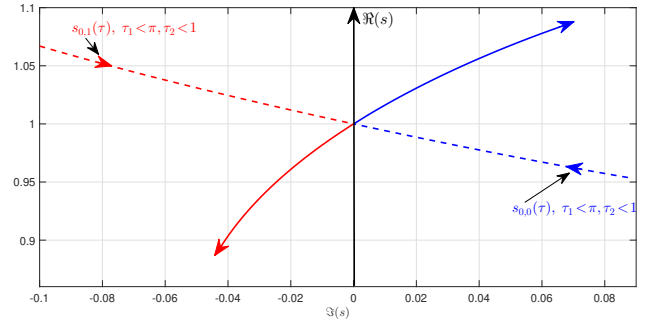


Fig. 3. Root locus of quasi-polynomial  $f(s, \tau)$  (18) around  $(i, \pi, 1)$ .

*Example 4.3:* Lets consider the special case of a model of population dynamics, see [16], with two distributed delays such that the characteristic functions is given by

$$f(s, \tau_1, \tau_2) = s - a \frac{1 - e^{-s\tau_1}}{s} - c \frac{1 - e^{-s\tau_2}}{s}, \quad (19)$$

with positive parameters  $a = -0.214104$ ,  $b = -0.996801$ . At  $(\tau_1^*, \tau_2^*) \approx (3.84003026849, 10.44866732901)$  the quasi-polynomial (19) posses a double root at  $s^* = i$ . We make a change of variable in order to shift the critical point to origin, obtaining  $\tilde{f}$ . The associated Weierstrass polynomial  $W(s, \tau) = s^2 + w_1(\tau) + w_0(\tau)$  can be computed, as a first approximation, by means of the first non zero partial derivatives using definition 3.1, given by

$$f_{0,(1,0)} \neq 0 \Rightarrow n_0^{(1)} = 1, \quad f_{0,(0,1)} \neq 0 \Rightarrow n_0^{(2)} = 1$$

$$f_{1,(1,0)} \neq 0 \Rightarrow n_1^{(1)} = 1, \quad f_{1,(0,1)} \neq 0 \Rightarrow n_1^{(2)} = 1$$

Now we are able to compute the first terms  $w_i(\tau)$  following Proposition 1.

$$w_0(\tau) = \alpha\tau_1 + \beta\tau_2 + \dots,$$

$$w_1(\tau) = \gamma\tau_1 + \delta\tau_2 + \dots,$$

with  $\alpha = (-0.0231801 + 0.0439373i)$ ,  $\beta = (0.00397688 - 0.0245988i)$ ,  $\gamma = (0.0105549 + 0.0292551i)$ ,  $\delta = (-0.0359858 + 0.150344i)$ . Applying Algorithm 1, to the Newton diagram  $\Pi = \Pi' \cup \Pi'' = \{(0, 0), (0, 1), (1, 0), (1, 1), (2, 0)\}$ , we get Table IV. By Proposition 7 the solutions of the polynomial



TABLE IV

RESULTS SUMMARY FOR THE QUASI-POLYNOMIAL 19.

Initial Data	Algorithm Output
$m = 2, \kappa = 0, \rho_0 = 0$	$r = 1, m_0 = 2, \beta_0 = 0$
$\Pi = \Pi' \cup \Pi''$	$\Pi^{(0)} = \{(0,0), (1,0), (2,0)\}$

$$\mathcal{P}(\xi) = \xi^2 + w_{1,(0,1)}\xi + w_{0,(1,0)}$$

determine the leading terms of the solutions. Taking in consideration the Newton diagram  $\Pi^{(0)}$ , we obtain Table V. Then, for  $\sigma = \{0, 1\}$ , the solutions are given by

TABLE V

RESULTS SUMMARY FOR THE QUASI-POLYNOMIAL 19.

Initial Data	Algorithm Output	$\mathcal{Z} := \{z \in \mathbb{C} : \mathcal{P}_j(\xi) = 0\}$
$m = 2, \kappa = 0, \rho_0 = 0$	$r = 1, m_0 = 2, \beta_0 = 0$	$\mathcal{P}_0(\xi) := \xi^2 + w_{0,(0,1)}$
$\Pi = \{(0,1), (1,1), (2,0)\}$	$\Pi^{(0)} = \{(0,1), (2,0)\}$	$\{c_{0,\sigma} = \pm\sqrt{w_{0,(0,1)}}\}$

$$s_{0,\sigma}(\boldsymbol{\tau}) = \pm(0.1202 - 0.1023i)(\tau_2 - \tau_2^*)^{1/2} + o\left(|\tau_1 - \tau_1^*|^{\frac{1}{2}}|\tau_2 - \tau_2^*|^{\frac{1}{2}}\right),$$

by Proposition 8 the solutions possess the CRS splitting property.

## V. CONCLUDING REMARKS

In this paper, we have considered some issues concerning the asymptotic behavior of multiple critical roots for quasi-polynomials with two delays. By means of the Weierstrass polynomial, the proposed approach is based on an iterative Newton diagram method which can be effectively applied to find the leading terms of power series solutions expressed as a generalized Puiseux series. Finally, the splitting properties of a given solution have been described by means of CRS, RS and NRS properties in order to get some insights about its geometric behavior.

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