

LIMIT CYCLES FOR m -PIECEWISE DISCONTINUOUS POLYNOMIAL LIÉNARD DIFFERENTIAL EQUATIONS

JAUME LLIBRE¹ AND MARCO ANTONIO TEIXEIRA²

ABSTRACT. We provide lower bounds for the maximum number of limit cycles for the m -piecewise discontinuous polynomial differential equations $\dot{x} = y + \operatorname{sgn}(g_m(x, y))F(x)$, $\dot{y} = -x$, where the zero set of the function $\operatorname{sgn}(g_m(x, y))$ with $m = 2, 4, 6, \dots$ is the product of $m/2$ straight lines passing through the origin of coordinates dividing the plane in sectors of angle $2\pi/m$, and $\operatorname{sgn}(z)$ denotes the sign function.

1. INTRODUCTION AND STATEMENT OF THE MAIN RESULT

Hilbert [9] in 1900 and in the second part of its 16–th problem proposed to find an estimation of the uniform upper bound for the number of limit cycles of all polynomial differential systems of a given degree, and also to study their distribution or configuration in the plane. Except for the Riemann hypothesis, the 16–th problem seems to be the most elusive of Hilbert’s problems. It has been one of the main problems in the qualitative theory of planar differential equations in the XX century. The contributions of Écalle [7] and Ilyashenko [10] proving that any polynomial differential system has finitely many limit cycles have been the best results in this area. But until now it is not proved the existence of an uniform upper bound. This problem remains open even for the quadratic polynomial differential systems. However, it is not difficult to see that any finite configuration of limit cycles is realizable for some polynomial differential system, see for details [13].

Thus we have the finiteness of the number of limit cycles for every polynomial differential system of degree n , but we do not have uniform

2010 *Mathematics Subject Classification.* 34C29, 34C25, 47H11.

Key words and phrases. limit cycle, Liénard equation, piecewise differential equation, averaging method.

* The first author is partially supported by a MICINN/FEDER grant MTM2008–03437, by a AGAUR grant number 2009SGR-0410 and by ICREA Academia. The second author is partially supported by a FAPESP–BRAZIL grant 2007/06896–5. All the authors are also supported by the joint project CAPES-MECD grant PHB-2009-0025-PC.

bounds for that number in the whole class of all polynomial differential systems of degree n . Following Smale [15] we consider an easier and special class of polynomial differential systems, the *Liénard polynomial differential systems*:

$$(1) \quad \begin{aligned} \dot{x} &= y + F(x), \\ \dot{y} &= -x, \end{aligned}$$

where $F(x) = a_0 + a_1x + \dots + a_nx^n$, and the dot denotes derivative with respect to the time t . For these systems the existence of uniform bounds also remains unproved. But when the degree n of these systems is odd Ilyashenko and Panov in [11] obtained an uniform upper bound for the number of limit cycles in a subclass of systems such that F is monic and its coefficients satisfy some estimations.

For the Liénard polynomial differential systems (1) Lins, de Melo and Pugh [12] in 1977 conjectured that they have at most $[(n-1)/2]$ limit cycles if $F(x)$ is a polynomial of degree n . Here $[z]$ denotes the integer part function of z . Moreover, he provided how to construct Liénard polynomial differential systems of degree n with $[(n-1)/2]$ limit cycles.

In 2007 Dumortier, Panazzolo and Roussarie [6] proved that for $n = 7$ there are 4 limit cycles when the conjecture stated at most 3. In fact as they comment in that paper their arguments can be extended in order to show that for $n \geq 7$ odd always there will be more limit cycles than the expected by the conjecture. Recently De Maesschalck and Dumortier proved in [4] that the classical Liénard equation of degree $n \geq 6$ can have $[(n-1)/2] + 2$ limit cycles. In the last two papers the discussions are based on singular perturbation theory, and the authors used relaxation oscillation solutions to study the number of limit cycles.

In short the results of Lins, de Melo and Pugh only show that $[(n-1)/2]$ is a lower bound for the maximum number of limit cycles that a Liénard polynomial differential systems (1) of degree n can have.

In this paper we shall study the limit cycles of the m -piecewise discontinuous polynomial differential equations

$$(2) \quad \begin{aligned} \dot{x} &= y + \operatorname{sgn}(g_m(x, y))F(x), \\ \dot{y} &= -x, \end{aligned}$$

where the zero set of the function $\operatorname{sgn}(g_m(x, y))$ with $m = 2, 4, 6, \dots$ is the product of $m/2$ straight lines passing through the origin of coordinates dividing the plane in sectors of angle $2\pi/m$. Here $\operatorname{sgn}(z)$ denotes

the sign function, i.e.

$$\operatorname{sgn}(z) = \begin{cases} -1 & \text{if } z < 0, \\ 0 & \text{if } z = 0, \\ 1 & \text{if } z > 0, \end{cases}$$

We also consider the case $m = 0$ with $g_0(x, y) = 1$. Therefore the differential equation (2) for $m = 0$ coincides with the Liénard polynomial differential equation (1). For this reason we shall call the m -piecewise discontinuous polynomial differential equations (2) for $m = 2, 4, 6, \dots$ as the *m -piecewise discontinuous Liénard polynomial differential equation of degree n* if n is the degree of the polynomial $F(x)$.

Piecewise discontinuous differential equations or more general non-smooth differential equations derived from ordinary differential equations when the non-uniqueness of some solutions is allowed. The theory of non-smooth differential equations has been developed very fast in these recent years due to various facts: its mathematical beauty, its strong relation with others branches of science and the challenge in establishing reasonable and consistent definitions and conventions. It has become certainly one of the common frontiers between Mathematics, Physics and Engineering. Also appears in a natural way in control systems, impact in mechanical systems and in nonlinear oscillations, in particular in electrical circuits. We understand that non-smooth systems are driven by applications and they play an intrinsic role in a wide range of technological areas. See for more details on the non-smooth differential equations [16] and the references therein.

Our main result on the limit cycles for m -piecewise discontinuous Liénard polynomial differential equations of degree n are the following theorem and conjecture.

Theorem 1. *Lower upper bounds $L(m, n)$ for the maximum number of limit cycles of the m -piecewise discontinuous polynomial Liénard differential equations (2) of degree n are*

$$L(0, n) = \left\lceil \frac{n-1}{2} \right\rceil, \quad L(2, n) = \left\lceil \frac{n}{2} \right\rceil, \quad L(4, n) = \left\lceil \frac{n-1}{2} \right\rceil.$$

Theorem 1 is proved in section 3 using the averaging theory. In the appendix we shall summarize the results on the averaging theory that we shall use in this paper. Of course the conjecture for $L(0, n)$ was proved by Lins, de Melo and Pugh [12], but here we shall present an easier and shorter proof using averaging theory.

Conjecture. *A lower upper bound $L(m, n)$ for the maximum number of limit cycles of the m -piecewise discontinuous polynomial Liénard*

differential equations of degree n is

$$L(m, n) = \left\lfloor \frac{1}{2} \left(n - \frac{m-2}{2} \right) \right\rfloor$$

if $m = 6, 8, 10, \dots$

In section 3 we shall provide some analytical results providing evidence that the conjecture must hold for the cases $L(m, n)$ with $m = 6, 8, 10, \dots$

2. COMPUTATIONS OF $L(0, n)$, $L(2, n)$ AND $L(4, n)$

As we shall see the proof of Theorem 1 is reduced to prove the next Propositions 2, 3 and 4.

First we shall provide the proof of $L(0, n)$. We recall the Descartes Theorem about the number of zeros of a real polynomial (for a proof see for instance [2]).

Descartes Theorem *Consider the real polynomial $p(x) = a_{i_1}x^{i_1} + a_{i_2}x^{i_2} + \dots + a_{i_r}x^{i_r}$ with $0 \leq i_1 < i_2 < \dots < i_r$ and $a_{i_j} \neq 0$ real constants for $j \in \{1, 2, \dots, r\}$. When $a_{i_j}a_{i_{j+1}} < 0$, we say that a_{i_j} and $a_{i_{j+1}}$ have a variation of sign. If the number of variations of signs is m , then $p(x)$ has at most m positive real roots. Moreover, it is always possible to choose the coefficients of $p(x)$ in such a way that $p(x)$ has exactly $r - 1$ positive real roots.*

Proposition 2. *The equality*

$$L(0, n) = \left\lfloor \frac{n-1}{2} \right\rfloor$$

holds.

Proof. For proving that $\lfloor (n-1)/2 \rfloor$ is a lower bound for the maximum number of limit cycles of the Liénard polynomial differential systems (1) of degree n , we shall prove that there are differential systems of the form

$$(3) \quad \begin{aligned} \dot{x} &= y + \varepsilon F(x), \\ \dot{y} &= -x, \end{aligned}$$

with $F(x) = a_0 + a_1x + \dots + a_nx^n$ and $a_n \neq 0$ having $\lfloor (n-1)/2 \rfloor$ limit cycles.

We consider the usual polar coordinates (r, θ) such that $x = r \cos \theta$ and $y = r \sin \theta$. The differential system (3) in polar coordinates becomes

$$(4) \quad \begin{aligned} \dot{r} &= \varepsilon \cos \theta F(r \cos \theta), \\ \dot{\theta} &= -1 - \varepsilon \frac{1}{r} \sin \theta F(r \cos \theta). \end{aligned}$$

Now taking as the new independent variable the variable θ , system (4) can be written as

$$(5) \quad \frac{dr}{d\theta} = -\varepsilon \cos \theta F(r \cos \theta) + O(\varepsilon^2) = \varepsilon f(\theta, r) + \varepsilon^2 g(\theta, r, \varepsilon).$$

Since the differential equation (5) satisfies all the assumptions of Theorem 10 of the appendix, we apply it to equation (5). Thus, using the notation of the appendix we have

$$\begin{aligned} f_0(r) &= \frac{1}{2\pi} \int_0^{2\pi} f(\theta, r) d\theta \\ &= -\frac{1}{2\pi} \int_0^{2\pi} \cos \theta F(r \cos \theta) d\theta \\ &= -\frac{1}{2\pi} \sum_{i=0}^n a_i r^i \int_0^{2\pi} \cos^{i+1} \theta d\theta \\ &= -\frac{1}{2\pi} \sum_{j=0}^{[(n-1)/2]} a_{2j+1} r^{2j+1} \int_0^{2\pi} \cos^{2j+2} \theta d\theta. \end{aligned}$$

If

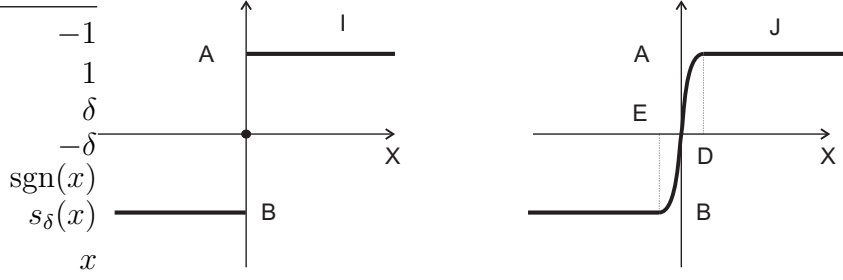
$$b_{2j+1} = -\frac{1}{2\pi} \int_0^{2\pi} \cos^{2j+2} \theta d\theta \neq 0$$

for $j = 0, 1, \dots, [(n-1)/2]$, it follows that

$$f_0(r) = \sum_{j=0}^{[(n-1)/2]} a_{2j+1} b_{2j+1} r^{2j+1}.$$

By Descartes Theorem and choosing the coefficients a_{2j+1} conveniently the polynomial $f_0(r)$ has $[(n-1)/2]$ positive roots r_k for $k = 1, 2, \dots, [(n-1)/2]$. Clearly the other roots of that polynomial of degree $2[(n-1)/2] + 1$ are 0 and $-r_k$ for $k = 1, 2, \dots, [(n-1)/2]$. Therefore $f'(r_k) \neq 0$ for $k = 1, 2, \dots, [(n-1)/2]$. Hence, by Theorem 10, for ε sufficiently small the differential equation (5), and consequently the differential system (3) will have $[(n-1)/2]$ limit cycles near the circles of radius r_k for $k = 1, 2, \dots, [(n-1)/2]$. Hence, the proposition is proved. \square

PSfrag replacements

FIGURE 1. The functions $\text{sign}(x)$ and $s_\delta(x)$.**Proposition 3.** *The equality*

$$L(2, n) = \left\lceil \frac{n}{2} \right\rceil$$

holds.

Proof. For proving that $\lceil n/2 \rceil$ is a lower bound for the maximum number of limit cycles of the 2-piecewise discontinuous Liénard polynomial differential systems (1) of degree n , we shall prove that there are differential systems of the form

$$(6) \quad \begin{aligned} \dot{x} &= y + \varepsilon \text{sgn}(x)F(x), \\ \dot{y} &= -x, \end{aligned}$$

with $F(x) = a_0 + a_1x + \dots + a_nx^n$ and $a_n \neq 0$ having $\lceil n/2 \rceil$ limit cycles.

System (6) in polar coordinates becomes

$$(7) \quad \begin{aligned} \dot{r} &= \varepsilon \text{sgn}(r \cos \theta) \cos \theta F(r \cos \theta), \\ \dot{\theta} &= -1 - \varepsilon \text{sgn}(r \cos \theta) \frac{1}{r} \sin \theta F(r \cos \theta). \end{aligned}$$

Instead of working with the discontinuous differential system (6) we shall work with the smooth differential system

$$(8) \quad \begin{aligned} \dot{x} &= y + \varepsilon s_\delta(x)F(x), \\ \dot{y} &= -x, \end{aligned}$$

where $s_\delta(x)$ is the smooth function defined in Figure 1, such that

$$\lim_{\delta \rightarrow 0} s_\delta(x) = \text{sgn}(x).$$

System (8) in polar coordinates becomes

$$(9) \quad \begin{aligned} \dot{r} &= \varepsilon s_\delta(r \cos \theta) \cos \theta F(r \cos \theta), \\ \dot{\theta} &= -1 - \varepsilon s_\delta(r \cos \theta) \frac{1}{r} \sin \theta F(r \cos \theta). \end{aligned}$$

We must note that the Poincaré map of both systems (7) and (9) are smooth, because in the first case it is composition of two smooth functions (one defined on $x = 0$ by the flow in $x > 0$, and the other also defined on $x = 0$ by the flow in $x < 0$), and in the second it is smooth by the general results on smooth ordinary differential equations. Clearly, the limit of the Poincaré map of system (8) when $\delta \rightarrow 0$ tends to the Poincaré map of system (6). On the other hand if we do the Taylor expansion of the Poincaré map in the parameter ε , the averaged function f_0 of the appendix is the coefficient of ε in such expansion, for more details see for instance the section 3 of [3]. Therefore, if $f_0^\delta(r)$ and $f_0(r)$ denotes the averaged function of systems (9) and (7) respectively, then the limit of $f_0^\delta(r)$ when $\delta \rightarrow 0$ is the function $f_0(r)$. Hence, by Theorem 10 the simple zeros of the function $f_0(r)$ provide limit cycles of the differential equation (7), and consequently of the discontinuous differential system (6). Now we shall compute the function $f_0(r)$.

Taking now θ as the new independent variable system (7) can be written as

$$(10) \quad \begin{aligned} \frac{dr}{d\theta} &= -\varepsilon \operatorname{sgn}(r \cos \theta) \cos \theta F(r \cos \theta) + O(\varepsilon^2) \\ &= \varepsilon f(\theta, r) + \varepsilon^2 g(\theta, r, \varepsilon). \end{aligned}$$

Since the differential equation (6) is the limit of systems satisfying all the assumptions of Theorem 10 of the appendix, we apply it to equation (10). Thus we have

$$\begin{aligned} f_0(r) &= \frac{1}{2\pi} \int_0^{2\pi} f(\theta, r) d\theta \\ &= \frac{1}{2\pi} \left(- \int_{-\pi/2}^{\pi/2} \cos \theta F(r \cos \theta) d\theta + \int_{\pi/2}^{3\pi/2} \cos \theta F(r \cos \theta) d\theta \right) \\ &= \frac{1}{2\pi} \int_{-\pi/2}^{\pi/2} (-\cos \theta F(r \cos \theta) d\theta + \cos(\theta - \pi) F(r \cos(\theta - \pi))) d\theta \\ &= -\frac{1}{2\pi} \int_{-\pi/2}^{\pi/2} (\cos \theta F(r \cos \theta) d\theta + \cos \theta F(-r \cos \theta)) d\theta \\ &= -\frac{1}{\pi} \sum_{j=0}^{[n/2]} a_{2j} r^{2j} \int_{-\pi/2}^{\pi/2} \cos^{2j+1} \theta d\theta. \end{aligned}$$

If

$$b_{2j} = -\frac{1}{\pi} \int_{-\pi/2}^{\pi/2} \cos^{2j+1} \theta d\theta < 0$$

for $j = 0, 1, \dots, [n/2]$, it follows that

$$f_0(r) = \sum_{j=0}^{[n/2]} a_{2j} b_{2j} r^{2j}.$$

By Descartes Theorem and choosing the coefficients a_{2j} conveniently the polynomial $f_0(r)$ has $[n/2]$ positive roots r_k for $k = 1, 2, \dots, [n/2]$. Clearly the other roots of that polynomial of degree $2[n/2]$ are $-r_k$ for $k = 1, 2, \dots, [n/2]$. Therefore $f'(r_k) \neq 0$ for $k = 1, 2, \dots, [n/2]$. Hence, from the previous arguments, by Theorem 10 for ε sufficiently small the differential equation (10), and consequently the differential system (6) will have $[n/2]$ limit cycles near the circles of radius r_k for $k = 1, 2, \dots, [n/2]$. Hence, the proposition is proved. \square

Proposition 4. *The equality*

$$L(4, n) = \left\lceil \frac{n-1}{2} \right\rceil$$

holds.

Proof. For proving that $[(n-1)/2]$ is a lower bound for the maximum number of limit cycles of the 4-piecewise discontinuous Liénard polynomial differential systems (1) of degree n , we shall prove that there are differential systems of the form

$$(11) \quad \begin{aligned} \dot{x} &= y + \varepsilon \operatorname{sgn}(x^2 - y^2) F(x), \\ \dot{y} &= -x, \end{aligned}$$

with $F(x) = a_0 + a_1x + \dots + a_nx^n$ and $a_n \neq 0$ having $[(n-1)/2]$ limit cycles.

System (11) in polar coordinates becomes

$$(12) \quad \begin{aligned} \dot{r} &= \varepsilon \operatorname{sgn}(\cos(2\theta)) \cos \theta F(r \cos \theta), \\ \dot{\theta} &= -1 - \varepsilon \operatorname{sgn}(\cos(2\theta)) \frac{1}{r} \sin \theta F(r \cos \theta). \end{aligned}$$

Using similar arguments to the proof of Proposition 3 we shall see that the discontinuous differential system (12) is limit in $\mathbb{R}^2 \setminus \{(0, 0)\}$ of smooth differential systems.

Taking θ as the new independent variable system (12) can be written as

$$(13) \quad \begin{aligned} \frac{dr}{d\theta} &= -\varepsilon \operatorname{sgn}(\cos(2\theta)) \cos \theta F(r \cos \theta) + O(\varepsilon^2) \\ &= \varepsilon f(\theta, r) + \varepsilon^2 g(\theta, r, \varepsilon). \end{aligned}$$

Since the differential equation (13) is the limit of systems satisfying all the assumptions of Theorem 10 of the appendix, we shall apply directly Theorem 10 to system (13) for computing the averaged function $f_0(r)$. Thus we have

$$f_0(r) = \frac{1}{2\pi} \int_0^{2\pi} f(\theta, r) d\theta = \frac{1}{2\pi} (I_1 + I_2),$$

where

$$\begin{aligned} I_1 &= - \int_{-\pi/4}^{\pi/4} \cos \theta F(r \cos \theta) d\theta - \int_{3\pi/4}^{5\pi/4} \cos \theta F(r \cos \theta) d\theta, \\ I_2 &= \int_{\pi/4}^{3\pi/4} \cos \theta F(r \cos \theta) d\theta + \int_{5\pi/4}^{7\pi/4} \cos \theta F(r \cos \theta) d\theta. \end{aligned}$$

We have

$$\begin{aligned} I_1 &= - \int_{-\pi/4}^{\pi/4} \cos \theta F(r \cos \theta) d\theta + \int_{-\pi/4}^{\pi/4} \cos \theta F(-r \cos \theta) d\theta \\ &= \int_{-\pi/4}^{\pi/4} \cos \theta (-F(r \cos \theta) + F(-r \cos \theta)) d\theta \\ &= -2 \sum_{j=0}^{[(n-1)/2]} a_{2j+1} r^{2j+1} \int_{-\pi/4}^{\pi/4} \cos^{2j+2} \theta d\theta \end{aligned}$$

If

$$b_{2j+1} = -2 \int_{-\pi/4}^{\pi/4} \cos^{2j+2} \theta d\theta < 0$$

for $j = 0, 1, \dots, [(n-1)/2]$, it follows that

$$I_1 = \sum_{j=0}^{[(n-1)/2]} a_{2j+1} b_{2j+1} r^{2j+1}.$$

Similarly we have

$$\begin{aligned} I_2 &= - \int_{\pi/4}^{3\pi/4} \cos \theta F(r \cos \theta) d\theta - \int_{\pi/4}^{3\pi/4} \cos \theta F(-r \cos \theta) d\theta \\ &= \int_{\pi/4}^{3\pi/4} \cos \theta (F(r \cos \theta) - F(-r \cos \theta)) d\theta \\ &= 2 \sum_{j=0}^{[(n-1)/2]} a_{2j+1} r^{2j+1} \int_{\pi/4}^{3\pi/4} \cos^{2j+2} \theta d\theta \end{aligned}$$

If

$$c_{2j+1} = 2 \int_{\pi/4}^{3\pi/4} \cos^{2j+2} \theta d\theta > 0$$

for $j = 0, 1, \dots, [(n-1)/2]$, it follows that

$$I_2 = \sum_{j=0}^{[(n-1)/2]} a_{2j+1} c_{2j+1} r^{2j+1}.$$

Consequently

$$2\pi f_0[r] = \sum_{j=0}^{[(n-1)/2]} a_{2j+1} (b_{2j+1} + c_{2j+1}) r^{2j+1}.$$

We claim that $b_{2j+1} + c_{2j+1} < 0$. This claim follows from the fact that if $\theta \in (-\pi/4, \pi/4)$ then $\cos \theta > 1/\sqrt{2}$, while if $\theta \in (\pi/4, 3\pi/4)$ then $\cos \theta < 1/\sqrt{2}$. Therefore, by Descartes Theorem and choosing the coefficients a_{2j+1} conveniently the polynomial $f_0(r)$ has $[(n-1)/2]$ positive roots r_k for $k = 1, 2, \dots, [(n-1)/2]$. Clearly the other roots of that polynomial of degree $2[(n-1)/2] + 1$ are 0 and $-r_k$ for $k = 1, 2, \dots, [(n-1)/2]$. Therefore $f'(r_k) \neq 0$ for $k = 1, 2, \dots, [(n-1)/2]$. Hence, by Theorem 10, for ε sufficiently small the differential equation (5), and consequently the differential system (3) will have $[(n-1)/2]$ limit cycles near the circles of radius r_k for \square

3. SOME ANALYTIC RESULTS AND NUMERICAL COMPUTATIONS

For $m = 2, 4, 6, \dots$ let $g_m(x, y)$ be the function which appears in system (2). The set of points (x, y) satisfying $g_m(x, y) = 0$, divides the plane in m sectors. We can assume that the slopes of the $m/2$ straight lines of $g_m(x, y) = 0$ are $\tan(\alpha + (2\pi j)/m)$ for $j = 0, 1, \dots, m/2 - 1$. Then, by the arguments of the proof of Propositions 3 and 4 for studying the limit cycles of the m -piecewise discontinuous Liénard polynomial differential equation of degree n via de averaging method we must study the simple zeros of the averaged function

$$f_0(r) = -\frac{1}{2\pi} \sum_{j=0}^{m-1} \int_{\alpha+(2\pi j)/m}^{\alpha+(2\pi(j+1))/m} (-1)^j \cos \theta F(r \cos \theta) d\theta.$$

If as usual $F(x) = a_0 + a_1x + \dots + a_nx^n$ with $a_n \neq 0$, then

$$(14) \quad \begin{aligned} f_0(r) &= -\frac{1}{2\pi} \sum_{i=0}^n a_i r^i \left(\sum_{j=0}^{m-1} \int_{\alpha+2\pi j/m}^{\alpha+2\pi(j+1)/m} (-1)^j \cos^{i+1} \theta d\theta \right) \\ &= \sum_{i=0}^n a_i d_i r^i. \end{aligned}$$

Consequently $f_0(r)$ always is a polynomial of degree at most n . Note that we have taken $(-1)^j$ in the expression of the function $f_0(r)$, but it also would be $(-1)^{j+1}$, this depends of the explicit expression of the function $g_m(x, y)$. But this change of sign in the function $f_0(r)$ does not affect its zeros.

Remark. From (14) for studying the simple zeros of the polynomial $f_0(r)$ we must know if the constants d_i which depend on m are zero or not. The problem of solving the conjecture is reduced to know which d_i are zero for a given m , and to apply the Descartes Theorem.

We recall that a function $g : \mathbb{R} \rightarrow \mathbb{R}$ is called *odd* if $g(-r) = -g(r)$, and it is called *even* if $g(-r) = g(r)$. If g is an odd polynomial, then g only has monomials of odd degree. If g is an even polynomial, then g only has monomials of even degree.

Proposition 5. *If m is multiple of 4, then $d_i = 0$ for $i = 0, 2, 4, \dots$, and the polynomial $f_0(r)$ is odd.*

Proof. Since m is multiple of 4, the signs $(-1)^j$ and $(-1)^{j+m/2}$ of $\text{sgn}(g_m(x, y))$ in an open sector defined by $g_m(x, y) = 0$ and in its symmetric with respect to the origin of coordinates are equal. But in one of these sectors $\cos^{i+1} \theta$ is positive and in the other negative because i is even. So the addition of the two integrals of d_i over these two symmetric sectors is zero, and consequently d_i holds. Therefore, from (14) it follows that $f_0(r)$ is an odd polynomial. \square

Proposition 6. *If m is not a multiple of 4, then $d_i = 0$ for $i = 1, 3, 5, \dots$, and the polynomial $f_0(r)$ is even.*

Proof. If m is not a multiple of 4, the signs $(-1)^j$ and $(-1)^{j+m/2}$ in an open sector and in its symmetric with respect to the origin of coordinates are different. Since in these two sectors $\cos^{i+1} \theta$ is positive because i is odd, again the addition of the two integrals of d_i over these two symmetric sectors is zero, and consequently d_i holds. Therefore, from (14) it follows that $f_0(r)$ is an even polynomial. \square

Of course the results of Propositions 5 and 6 agree with the expressions of $f_0(r)$ obtained in the proofs of Propositions 3 and 4.

Proposition 7. *If $m = 6$ then*

$$f_0(r) = \sum_{j=1}^{\lfloor n/2 \rfloor} a_{2j} d_{2j} r^{2j}.$$

Moreover the maximum number of positive real roots of the polynomial $f_0(r)$ is $\lfloor (n-2)/2 \rfloor$.

Proof. From Proposition 6 and (14) it follows that for $m = 6$ we have

$$f_0(r) = \sum_{j=0}^{\lfloor n/2 \rfloor} a_{2j} d_{2j} r^{2j}.$$

We must prove that $d_0 = 0$. We have that

$$\begin{aligned} d_0 &= \frac{1}{2\pi} \sum_{j=0}^5 \int_{\alpha+\pi j/3}^{\alpha+\pi(j+1)/3} (-1)^{j+1} \cos \theta d\theta \\ &= \frac{1}{2\pi} \int_{\alpha}^{\alpha+\pi/3} \sum_{j=0}^5 (-1)^{j+1} \cos \left(\theta - \frac{j\pi}{3} \right) d\theta \end{aligned}$$

An easy computation shows that

$$\sum_{j=0}^5 (-1)^{j+1} \cos \left(\theta - \frac{j\pi}{3} \right) = 0,$$

consequently $d_0 = 0$.

Now the rest of the proof follows using Descartes Theorem as at the end of the proof of Proposition 3. \square

Note that for proving the conjecture for $m = 6$, from Proposition 7, we only need to show that $d_{2j} \neq 0$ for $j = 1, 2, 3, \dots$, and apply the arguments of the end of the proof of Proposition 3.

With the help of the program mathematica we obtain for $m = 6$ and $\alpha = \pi/2$ that

$$d_{2j} = \frac{1}{\pi} \left(2B_{\frac{3}{4}} \left(j+1, \frac{1}{2} \right) - \frac{\sqrt{\pi} \Gamma(j+1)}{\Gamma(j+\frac{3}{2})} \right)$$

where $B_{\frac{3}{4}}(a, b)$ is an incomplete beta function and $\Gamma(z)$ is the Euler gamma function, for more details see [1]. Then, again we can verify that $d_0 = 0$, and we must compute d_{2j} for many $j \in \{1, 2, 3, \dots\}$ and check that for those $d_{2j} \neq 0$. But we do not know how to prove that $d_{2j} \neq 0$ for all $j = 1, 2, 3, \dots$. If this can be proved then the conjecture is proved for $m = 6$.

Proposition 8. *If $m = 8$ then*

$$f_0(r) = \sum_{j=1}^{[(n-1)/2]} a_{2j+1} d_{2j+1} r^{2j+1}.$$

Moreover the maximum number of positive real roots of the polynomial $f_0(r)$ is $[(n-3)/2]$.

Proof. From Proposition 5 and (14) it follows that for $m = 6$ we have

$$f_0(r) = \sum_{j=0}^{[(n-1)/2]} a_{2j+1} d_{2j+1} r^{2j+1}.$$

We must prove that $d_1 = 0$. We have that

$$\begin{aligned} d_1 &= \frac{1}{2\pi} \sum_{j=0}^7 \int_{\alpha+\pi j/4}^{\alpha+\pi(j+1)/4} (-1)^{j+1} \cos^2 \theta d\theta \\ &= \frac{1}{2\pi} \int_{\alpha}^{\alpha+\pi/4} \sum_{j=0}^7 (-1)^{j+1} \cos^2 \left(\theta - \frac{j\pi}{4} \right) d\theta \end{aligned}$$

An easy computation shows that

$$\sum_{j=0}^7 (-1)^{j+1} \cos^2 \left(\theta - \frac{j\pi}{4} \right) = 0,$$

consequently $d_1 = 0$.

Now the rest of the proof follows using Descartes Theorem as in the end of the proof of Proposition 4. \square

Again note that for proving the conjecture for $m = 8$, from Proposition 8, we only need to show that $d_{2j+1} \neq 0$ for $j = 1, 2, 3, \dots$, and apply the arguments of the end of the proof of Proposition 4.

Again using the program mathematica we obtain for $m = 8$ and $\alpha = \pi/8$ that

$$\begin{aligned} d_{2j+1} &= \frac{1}{\pi \Gamma(j+2)} \left(\sqrt{\pi} \Gamma\left(j + \frac{3}{2}\right) + 2 \left(B_{\frac{1}{4}(2-\sqrt{2})}\left(j + \frac{3}{2}, \frac{1}{2}\right) - \right. \right. \\ &\quad \left. \left. B_{\frac{1}{4}(2+\sqrt{2})}\left(j + \frac{3}{2}, \frac{1}{2}\right) \right) \Gamma(j+2) \right). \end{aligned}$$

Then, we can verify that $d_1 = 0$, and we can compute d_{2j+1} for many $j \in \{1, 2, 3, \dots\}$ and check that for those $d_{2j+1} \neq 0$. But again we do not know how to prove that $d_{2j+1} \neq 0$ for all $j = 1, 2, 3, \dots$. If this can be proved then the conjecture is proved for $m = 8$.

Proposition 9. *If $m = 10$ then*

$$f_0(r) = \sum_{j=2}^{[n/2]} a_{2j} d_{2j} r^{2j}.$$

Moreover the maximum number of positive real roots of the polynomial $f_0(r)$ is $[(n-4)/2]$.

Proof. From Proposition 6 and (14) it follows that for $m = 10$ we have

$$f_0(r) = \sum_{j=0}^{[n/2]} a_{2j} d_{2j} r^{2j}.$$

We must prove that $d_0 = d_2 = 0$. We have that

$$\begin{aligned} d_0 &= \frac{1}{2\pi} \sum_{j=0}^9 \int_{\alpha+\pi j/5}^{\alpha+\pi(j+1)/5} (-1)^{j+1} \cos \theta d\theta \\ &= \frac{1}{2\pi} \int_{\alpha}^{\alpha+\pi/5} \sum_{j=0}^9 (-1)^{j+1} \cos \left(\theta - \frac{j\pi}{5} \right) d\theta \end{aligned}$$

An easy computation shows that

$$\sum_{j=0}^9 (-1)^{j+1} \cos \left(\theta - \frac{j\pi}{5} \right) = 0,$$

consequently $d_0 = 0$.

On the other hand

$$\begin{aligned} d_2 &= \frac{1}{2\pi} \sum_{j=0}^9 \int_{\alpha+\pi j/5}^{\alpha+\pi(j+1)/5} (-1)^{j+1} \cos^3 \theta d\theta \\ &= \frac{1}{2\pi} \int_{\alpha}^{\alpha+\pi/5} \sum_{j=0}^9 (-1)^{j+1} \cos^3 \left(\theta - \frac{j\pi}{5} \right) d\theta \end{aligned}$$

An easy computation shows that

$$\sum_{j=0}^9 (-1)^{j+1} \cos^3 \left(\theta - \frac{j\pi}{5} \right) = 0,$$

consequently $d_2 = 0$.

Now the rest of the proof follows using Descartes Theorem as in the end of the proof of Proposition 3. \square

Note that for proving the conjecture for $m = 6$, from Proposition 7, we only need to show that $d_{2j} \neq 0$ for $j = 1, 2, 3, \dots$, and apply the arguments of the end of the proof of Proposition 3.

With the program mathematica we obtain for $m = 10$ and $\alpha = \pi/2$ that

$$d_{2j} = \frac{1}{\pi} \left[2B_{\frac{1}{8}(5-\sqrt{5})} \left(j+1, \frac{1}{2} \right) - 2B_{\frac{1}{8}(5+\sqrt{5})} \left(j+1, \frac{1}{2} \right) + \frac{\sqrt{\pi}\Gamma(j+1)}{\Gamma(j+\frac{3}{2})} \right].$$

Then, again we can verify that $d_0 = d_2 = 0$, and we can compute d_{2j} for many $j \in \{2, 3, \dots\}$ and check that for those $d_{2j} \neq 0$. But we do not know how to prove that $d_{2j} \neq 0$ for all $j = 2, 3, \dots$. If this can be proved then the conjecture is proved for $m = 10$, and so on.

APPENDIX I: AVERAGING THEORY OF FIRST ORDER

We first briefly recall the basic elements of averaging theory that we shall need in this paper. Roughly speaking, the method gives a quantitative relation between the solutions of a non-autonomous periodic differential system and the solutions of its averaged differential system, which is autonomous. The following theorem provides a first order approximation for periodic solutions of the original system (for a proof see for example [8, 14, 17]).

We consider the initial value problems

$$(15) \quad \dot{\mathbf{x}} = \varepsilon f(t, \mathbf{x}) + \varepsilon^2 g(t, \mathbf{x}, \varepsilon), \quad \mathbf{x}(0) = \mathbf{x}_0,$$

and

$$(16) \quad \dot{\mathbf{y}} = \varepsilon f_0(\mathbf{y}), \quad \mathbf{y}(0) = \mathbf{x}_0,$$

with f , \mathbf{y} and \mathbf{x}_0 in some open subset Ω of \mathbb{R}^n , $t \in [0, \infty)$, $\varepsilon \in (0, \varepsilon_0]$. Here ε is a small parameter. We assume that f and g are periodic of period T in the variable t , and we set

$$f_0(\mathbf{y}) = \frac{1}{T} \int_0^T f(t, \mathbf{y}) dt.$$

Theorem 10. *Assume that f , $D_{\mathbf{x}}f$, $D_{\mathbf{x}\mathbf{x}}f$ and $D_{\mathbf{x}}g$ are continuous and bounded by a constant independent of ε in $[0, \infty) \times \Omega \times (0, \varepsilon_0]$, and that $\mathbf{y}(t) \in \Omega$ for $t \in [0, 1/\varepsilon]$. Then the following statements holds.*

- (1) *For $t \in [0, 1/\varepsilon]$ we have $\mathbf{x}(t) - \mathbf{y}(t) = O(\varepsilon)$ as $\varepsilon \rightarrow 0$.*
- (2) *If $p \neq 0$ is a singular point of system (16) and $\det D_{\mathbf{y}}F(p) \neq 0$, then there exists a periodic solution $\phi(t, \varepsilon)$ of period T for system (15) which is close to p , more precisely $\phi(0, \varepsilon) - p = O(\varepsilon)$ as $\varepsilon \rightarrow 0$.*

- (3) *The stability of the periodic solution $\phi(t, \varepsilon)$ is given by the stability of the singular point.*

We have used the notation $D_{\mathbf{x}}f$ for all the first derivatives of f , and $D_{\mathbf{xx}}f$ for all the second derivatives of f .

APPENDIX II: AN EXAMPLE IN CONTROL SYSTEMS

The constants in the following model can be chosen in such a way that it fits in the universe of systems treated in this paper.

Consider the second order equation

$$\ddot{x} + a\dot{x} + bx = \varepsilon\alpha x$$

with a, b arbitrary constants, ε a real parameter, and α satisfying $|\alpha| \leq 1$.

Let Z_α be the vector field represented by

$$\begin{aligned}\dot{x} &= y, \\ \dot{y} &= -bx - ay + \varepsilon\alpha x.\end{aligned}$$

Note that, when $\varepsilon = 0$, $a^2 - 4b < 0$ and $a \neq 0$ then the system becomes a linear vector field with complex eigenvalues (when $a = 0$ the system becomes a center).

Let $v = v(x, y)$ be a smooth real function defined in the plane and we want to find α that minimizes the derivative of v along the orbits of Z_α . So,

$$\dot{v} = yv_x - (bx + ay)v_y + \varepsilon\alpha xv_y,$$

and $\min\{\dot{v}\}$ is attained by setting

$$\alpha_0 = \operatorname{sgn}\{x.v_y\}$$

Choosing $v = (x^2 + xy + y^2)/2$ we consider Z_{α_0} with $\alpha_0 = \operatorname{sgn}\{x(x+y)\}$. So this system can be represented by the following differential system

$$\begin{aligned}\dot{x} &= y, \\ \dot{y} &= -bx - ay + \varepsilon x,\end{aligned}$$

if $x(x+y) > 0$ and

$$\begin{aligned}\dot{x} &= y, \\ \dot{y} &= -bx - ay - \varepsilon x,\end{aligned}$$

if $x(x+y) < 0$.

Assume Z_{α_0} satisfying the Filippov rules on the straight lines $L_1 : \{x = 0\}$ and $L_2 : \{x + y = 0\}$, which divide the plane in four regions I, II, III and IV.

If $(1 - b - a)^2 > \varepsilon^2$ then the orbits of the system spiral the singularity 0. Observe that on the discontinuity set one finds just sewing regions.

REFERENCES

- [1] M. ABRAMOWITZ AND I.A. STEGUN, *Handbook of mathematical functions with formulas, graphs, and mathematical tables*, National Bureau of Standards Applied Mathematics Series **55**, Washington, 1964.
- [2] I.S. BEREZIN AND N.P. ZHIDKOV, *Computing Methods*, Volume II, Pergamon Press, Oxford, 1964.
- [3] A. BUICA AND J. LLIBRE, *Averaging methods for finding periodic orbits via Brouwer degree*, Bulletin des Sciences Mathématiques **128** (2004), 7–22.
- [4] P. DE MAESSCHALCK AND F. DUMORTIER, *Classical Liénard equation of degree $n \geq 6$ can have $\lfloor \frac{n-1}{2} \rfloor + 2$ limit cycles*, J. Differential Equations **250** (2011), 2162–2176.
- [5] F. DUMORTIER, J. LLIBRE AND J.C. ARTÉS, *Qualitative theory of planar differential systems*, UniversiText, Springer–Verlag, New York, 2006.
- [6] F. DUMORTIER, D. PANAZZOLO AND R. ROUSSARIE, *More limit cycles than expected in Liénard equations*, Proc. Amer. Math. Soc. **135** (2007), 1895–1904.
- [7] J. ÉCALLE, *Introduction aux fonctions analysables et preuve constructive de la conjecture de Dulac*, Hermann, 1992.
- [8] J. GUCKENHEIMER AND P. HOLMES, *Nonlinear oscillations, dynamical systems and bifurcations of vectors fields*, Springer, 1983.
- [9] D. HILBERT, *Mathematische Probleme*, Lecture, Second Internat. Congr. Math. (Paris, 1900), *Nachr. Ges. Wiss. Göttingen Math. Phys. Kl.* (1900), 253–297; English transl., *Bull. Amer. Math. Soc.* **8** (1902), 437–479.
- [10] YU. ILYASHENKO, *Finiteness Theorems for Limit Cycles*, Translations of Math. Monographs **94**, Amer. Math. Soc., 1991.
- [11] YU. ILYASHENKO AND A. PANOV, *Some upper estimates of the number of limit cycles of planar vector fields with applications to Liénard equations*, Moscow Math. J. **1** (2001), 583–599.
- [12] A. LINS, W. DE MELO AND C.C. PUGH, *On Liénard’s Equation*, Lecture Notes in Math. **597**, Springer, Berlin, 1977, pp 335–357.
- [13] J. LLIBRE AND G. RODRÍGUEZ, *Configurations of limit cycles and planar polynomial vector fields*, J. of Differential Equations **198** (2004), 374–380.
- [14] J. SANDERS AND F. VEHRULST, *Averaging method in nonlinear dynamical systems*, Applied Mathematical Sciences. **59**, Springer, 1985.
- [15] S. SMALE, *Mathematical Problems for the Next Century*, Mathematical Intelligencer **20**, (1998), 7–15.
- [16] M.A. TEIXEIRA, *Perturbation theory for non-smooth systems*, in Encyclopedia of complexity and systems science, R. A. Meyers and G. Gaeta, Eds. Springer–Verlag, New York, 2009, pp. 6697–6709.
- [17] F. VEHRULST, *Nonlinear differential equations and dynamical systems*, Universitext, Springer, 1996.

¹ DEPARTAMENT DE MATEMÀTIQUES, UNIVERSITAT AUTÒNOMA DE BARCELONA, 08193 BELLATERRA, BARCELONA, CATALONIA, SPAIN

² DEPARTAMENTO DE MATEMÁTICA, UNIVERSIDADE ESTADUAL DE CAMPINAS, CAIXA POSTAL 6065, 13083–970, CAMPINAS, SP, BRAZIL

E-mail address: jllibre@mat.uab.cat

E-mail address: teixeira@ime.unicamp.br