

NEW CLASSES OF POLYNOMIAL MAPS SATISFYING THE REAL JACOBIAN CONJECTURE IN \mathbb{R}^2

JACKSON ITIKAWA¹ AND JAUME LLIBRE²

ABSTRACT. We present two new classes of polynomial maps satisfying the real Jacobian conjecture in \mathbb{R}^2 . The first class is formed by the polynomial maps of the form $(q(x) - p(y), q(y) + p(x)) : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ such that p and q are real polynomials satisfying $p'(x)q'(x) \neq 0$. The second class is formed by polynomial maps $(f, g) : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ where f and g are real homogeneous polynomials of the same arbitrary degree satisfying some conditions.

1. INTRODUCTION AND STATEMENT OF THE MAIN RESULTS

Let $F = (f, g) : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ be a polynomial map such that its Jacobian never vanishes. The celebrated *real Jacobian conjecture* states that under these conditions F is injective. This conjecture goes back to 1939, see Keller [6].

In 1994 Pinchuk [7] found a map $F = (f, g)$ with f and g polynomials of degree 10 and 25 respectively, and with Jacobian strictly positive, such that F is not injective.

Although the real Jacobian conjecture has been proved false by Pinchuk, a considerable number of papers has been devoted to this subject, mainly searching for additional conditions such that the conjecture might hold. The problem of determining if F is injective in the case of its Jacobian to be a non-zero constant, known as the *Jacobian conjecture*, is still open, see [9] and the references therein for more information.

In this note we present two new classes of polynomial maps that satisfies the real Jacobian conjecture. In what follows we present our main results.

2010 *Mathematics Subject Classification.* Primary 14R15, 34C25, 37C05, 37C10, 37J45.

Key words and phrases. injective polynomial maps, global center, real Jacobian conjecture, planar Hamiltonian systems.

Theorem 1. *Let p and q be real polynomials of one variable and consider the polynomial map $F = (f, g) : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ with $f = f(x, y) = q(x) - p(y)$, $g = g(x, y) = q(y) + p(x)$ and $p'(x)q'(x) \neq 0$. Then the Jacobian of polynomial map F never vanish and F is injective.*

Theorem 1 is proved in section 4.

As usual here $p'(x)$ denotes the derivative of p with respect to the variable x , and if $f = f(x, y)$ we denote by f_x the partial derivative of f with respect to the variable x . Similarly is defined f_y .

Theorem 2. *Let f and g be real homogeneous polynomials of the same degree in the variables x and y such that*

- (i) *the Jacobian of the polynomial map $F = (f, g) : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ never vanish,*
- (ii) *f and g has no real linear factors in common,*
- (iii) *the polynomials $P = -ff_y - gg_y$ and $Q = ff_x + gg_x$ have no real common factors, and*
- (iv)
$$\int_{-\infty}^{+\infty} \frac{P(1, y)}{Q(1, y) - yP(1, y)} dy = 0.$$

Then the polynomial map F is injective.

Theorem 2 is also proved in section 4.

Other classes of polynomial maps satisfying the real Jacobian conjecture were given in [1, 2].

2. PRELIMINARY RESULTS

Let P and Q be polynomials in the variables x and y . Consider the polynomial differential system

$$\dot{x} = P(x, y), \quad \dot{y} = Q(x, y). \quad (1)$$

We say that an isolated singularity p of system (1) is a *center* when there is a neighborhood $V_p \subset U$ of p such that every solution in $V_p \setminus \{p\}$ is periodic. The biggest open connected set containing p , denoted by $W_p \subset U$, such that $W_p \setminus \{p\}$ is filled with periodic orbits is called the *period annulus of the center*. If $W_p = \mathbb{R}^2$ then p is a *global center* of system (1).

Let q be an isolated singularity of system (1). If $X = (P, Q)$ then $DX(q)$ is the Jacobian matrix of system (1) at q . If $\det(DX(q)) \neq 0$

then we say that q is a *non-degenerate singular point*. Under these assumptions a necessary condition in order that q be a center is that the eigenvalues of $DX(q)$ are purely imaginary. Such a center is a *non-degenerate center*.

The polynomial differential system (1) is a *Hamiltonian system* if there is a polynomial H such that $P(x, y) = -H_y(x, y)$ and $Q(x, y) = H_x(x, y)$. Then the polynomial H is called the *Hamiltonian* of the Hamiltonian system (1).

The following result is due to Sabatini, see Theorem 2.3 of [8]. This result provides a relation between the real Jacobian conjecture and the global centers of some polynomial Hamiltonian systems.

Theorem 3. *Let $F = (f, g) : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ be a polynomial map such that its Jacobian never vanishes and $F(0, 0) = (0, 0)$. Then the following statements are equivalent.*

- (a) *The polynomial Hamiltonian system with Hamiltonian $H = (f(x, y)^2 + g(x, y)^2)/2$ has a global center at the origin of coordinates.*
- (b) *The map F is a global diffeomorphism of \mathbb{R}^2 onto itself.*

In addition we present the following result due to Braun and Llibre, see Lemma 1 of [3].

Lemma 4. *Let $F = (f, g) : U \rightarrow \mathbb{R}^2$ be a \mathcal{C}^2 function defined in an open connected set $U \subset \mathbb{R}^2$ and $(x_0, y_0) \in U$ such that the Jacobian of F in (x_0, y_0) does not vanish. Moreover consider the Hamiltonian $H = (f(x, y)^2 + g(x, y)^2)/2$. Then (x_0, y_0) is a singular point of the polynomial Hamiltonian system $\dot{x} = -H_y$, $\dot{y} = H_x$ if and only if $F(x_0, y_0) = (0, 0)$. Under these conditions (x_0, y_0) is a non-degenerate center and also an isolated global minimum of H . In particular if the Jacobian of F never vanishes in U all the singular points of the Hamiltonian system $\dot{x} = -H_y$, $\dot{y} = H_x$ in U are non-degenerate centers and are the zeros of the map F .*

3. THE POINCARÉ COMPACTIFICATION

The set $\mathbb{S}^2 = \{y = (y_1, y_2, y_3) \in \mathbb{R}^3 : y_1^2 + y_2^2 + y_3^2 = 1\}$ is called the *Poincaré sphere*. Consider $T_y\mathbb{S}^2$ the tangent space to the Poincaré sphere at the point y and the central projection $f : T_{(0,0,1)}\mathbb{S}^2 \rightarrow \mathbb{S}^2$.

Let X be a polynomial vector field of degree n in the plane $T_{(0,0,1)}\mathbb{S}^2$. The map f defines 2 copies of X in \mathbb{S}^2 , one in the northern hemisphere and the other in the southern hemisphere. Let X' be the vector field

$Df \circ X$ defined on the Poincaré sphere except on its equator $\mathbb{S}^1 = \{y \in \mathbb{S}^2 : y_3 = 0\}$. We remark that X' is everywhere tangent to \mathbb{S}^2 and \mathbb{S}^1 is identified to the infinity of \mathbb{R}^2 . We define $p(X)$, the *Poincaré compactified vector field associated to X* as the analytic extension of $y_3^{n-1}X'$ to \mathbb{S}^2 . Note that studying the behavior of $p(X)$ around \mathbb{S}^1 , we obtain the behavior of X at infinity. Also, \mathbb{S}^1 is invariant under the flow of $p(X)$.

The *Poincaré disc* is the projection of the closed northern hemisphere of \mathbb{S}^2 on $y_3 = 0$ under $(y_1, y_2, y_3) \mapsto (y_1, y_2)$.

The singular points of $p(X)$ in the interior of the Poincaré disc, or equivalently in open northern hemisphere $\{(y_1, y_2, y_3) \in \mathbb{S}^2 : y_3 > 0\}$, are called the *finite singular points* of X . While the singular points of $p(X)$ contained in \mathbb{S}^1 are called the *infinite singular points* of X .

For more details on the Poincaré compactification, see chapter 5 of [5].

The following result is the Poincaré–Hopf Theorem for the Poincaré compactification of a polynomial vector field. For a proof see for instance Theorem 6.30 of [5].

Theorem 5. *Let X be a polynomial vector field. If $p(X)$ defined on the Poincaré sphere \mathbb{S}^2 has finitely many singular points, then the sum of their topological indices is two.*

4. PROOFS OF THE THEOREMS

Proof of Theorem 1. Since the Jacobian of F is $q'(x)q'(y) + p'(x)p'(y) > 0$, because $p'(x)q'(y)$ never vanishes, we have that the polynomial map $F = (f, g)$ with $f = q(x) - p(y)$, $g = q(y) + p(x)$ satisfies the assumptions of Lemma 4 with $U = \mathbb{R}^2$. Hence all the singular points of the polynomial Hamiltonian system with Hamiltonian $H = (f(x, y)^2 + g(x, y)^2)/2$ are non-degenerated centers.

We study the infinite singular points of the system

$$\dot{x} = P = -H_y = -ff_y - gg_y, \quad \dot{y} = Q = H_x = ff_x + gg_x, \quad (2)$$

where $f = q(x) - p(y)$, $g = q(y) + p(x)$ with $p(x) = ax^n + l.o.t.$, $q(x) = bx^m + l.o.t.$, n and m positive integers, $ab \neq 0$, and *l.o.t.* means lower order terms of the polynomial.

First we assume that $n = m$. For studying the infinite equilibria consider the homogeneous polynomial $yP_{2n-1}(x, y) - xQ_{2n-1}(x, y)$ of

degree $2n$, where P_{2n-1} and Q_{2n-1} are the homogeneous parts of degree $2n-1$ of the polynomials P and Q respectively.

Since $yP_{2n-1}(x, y) - xQ_{2n-1}(x, y) = -n(a^2 + b^2)(x^{2n} + y^{2n}) \neq 0$ for $(x, y) \neq (0, 0)$, the Hamiltonian system (2) has no infinite singular points.

For the cases $n > m$ and $n < m$ we have respectively $yP_{2n-1}(x, y) - xQ_{2n-1}(x, y) = -na^2(x^{2n} + y^{2n}) \neq 0$ and $yP_{2m-1}(x, y) - xQ_{2m-1}(x, y) = -mb^2(x^{2m} + y^{2m}) \neq 0$ for $(x, y) \neq (0, 0)$. Therefore again the Hamiltonian system has no infinite singular points, and \mathbb{S}^1 is a periodic orbit of the Poincaré compactification of system (2).

By the Poincaré–Hopf Theorem (Theorem 5) applied to the Poincaré sphere and since there are no infinite singular points the sum of the indices of all the finite singular points is one. Therefore there exists a unique center, which we denote by c .

To end the proof applying Theorem 3 we must prove that the local center c is global. Let W_c be the period annulus of c . If the last periodic orbit of W_c is the infinity in the Poincaré disc we are done.

Assume that γ is the last periodic orbit of W_c and that it does not coincide with the periodic orbit at \mathbb{S}^1 , and let p be a point of γ . Consider the Poincaré map $\Pi : \Sigma_0 \rightarrow \Sigma$ associated to γ , where Σ is a local transverse section to the vector field associated to system (2) through the point p , for further information on these topics see chapter 1 of [5]. Here Σ_0 denotes the domain of definition of the map Π on the section Σ .

By Proposition 1.21 of [5] the map Π is analytic because system (2) is polynomial. Clearly the map Π restricted to the part of Σ_0 contained in the period annulus W_c is the identity. Therefore, since Π is an analytic map of one variable, it is analytic in the whole Σ_0 . Hence γ cannot be the last periodic orbit of W_c , a contradiction. Consequently the center is global and by Theorem 3 we conclude that $F = (f, g)$ is injective. \square

Proposition 4.2 of [4] states:

Proposition 6. *Let P and Q be two real homogeneous polynomials of degree n in the variables x and y . Assume that P and Q do not have real common factors, that $xQ(x, y) - yP(x, y)$ has no real linear factors, and that*

$$\int_{-\infty}^{+\infty} \frac{P(1, y)}{Q(1, y) - yP(1, y)} dy = 0.$$

Then the phase portrait of the polynomial vector field (P, Q) is a global center.

Proof of Theorem 2. Under the assumptions of Theorem 2, first we shall see that the polynomial $xQ(x, y) - yP(x, y)$ has no real linear factors. By the Euler's Theorem for homogeneous functions we have that

$$xQ - yP = x(ff_x + gg_x) + y(ff_y + gg_y) = n(f^2 + g^2).$$

Therefore since the homogeneous polynomials f and g has no real linear factors in common, the homogeneous polynomial $xQ(x, y) - yP(x, y)$ also does not have a real linear factor. Hence, from the hypotheses of Theorem 2 all the assumptions of Proposition 6 are satisfied. Consequently the Hamiltonian system with Hamiltonian $H = (f^2 + g^2)/2$ has a global center. So by Theorem 3 we get that the polynomial map $F = (f, g)$ is injective. \square

ACKNOWLEDGEMENTS

The first author is supported by a FAPESP grant number 2016/23285-9. The second author is supported by a MINECO-FEDER grant MTM2016-77278-P, a MINECO grant MTM2013-40998-P, and an AGAUR grant number 2014SGR-568.

REFERENCES

- [1] F. BRAUN AND J. LLIBRE, *Sufficient conditions in order that the real Jacobian conjecture in \mathbb{R}^2 holds*, Anais da Academia Brasileira de Ciências **87** (2015), 1519–1524.
- [2] F. BRAUN AND J. LLIBRE, *A sufficient condition in order that the real Jacobian conjecture in \mathbb{R}^2 holds*, J. Differential Equations **260** (2016), 5250–5258.
- [3] F. BRAUN AND J. LLIBRE, *On the connection between global centers and global injectivity*, Preprint, 2017, arXiv:1706.02643.
- [4] A. CIMA AND J. LLIBRE, *Algebraic and topological classification of the homogeneous cubic vector fields in the plane*, J. of Math. Anal. and Appl. **147** (1990), 420–448.
- [5] F. DUMORTIER, J. LLIBRE AND J.C. ARTÉS, *Qualitative theory of planar differential systems*, Universitext, Springer-Verlag, 2006.
- [6] O.H. KELLER, *Ganze Cremona-Transformationen*, Monatsh. Math. Phys. **17** (1939), 299–306.
- [7] S. PINCHUK, *A counterexample to the strong real Jacobian conjecture*, Math. Z. **217** (1994), 1–4.
- [8] M. SABATINI, *A connection between isochronous Hamiltonian centres and the Jacobian Conjecture*, Nonlinear Anal. **34** (1998), 829–838.

- [9] A. VAN DEN ESSEN, *Polynomial automorphisms and the Jacobian conjecture*, Progress in Mathematics **190**, Birkhäuser Verlag.

¹DEPARTAMENT OF MATHEMATICS, ICMC USP, SÃO CARLOS, SP 13566-590, BRAZIL

E-mail address: itikawa@icmc.usp.br

² DEPARTMENT DE MATEMÀTIQUES, UNIVERSITAT AUTÒNOMA DE BARCELONA, 08193 BELLATERRA (BARCELONA)

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