Four limit cycles from perturbing quadratic integrable systems by quadratic polynomials

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Abstract

In this paper, we give a positive answer to the open question: Can there exist 4 limit cycles in quadratic near-integrable polynomial systems? It is shown that when a quadratic integrable system has two centers and is perturbed by quadratic polynomials, it can generate at least 4 limit cycles with (3, 1) distribution. The method of Melnikov function is used.

Keywords: Hilbert’s 16th problem, quadratic near-integrable system, limit cycle, reversible system, Hopf bifurcation, Poincaré bifurcation, Melnikov function

MSC: 34C07; 34C23

1 Introduction

The well-known Hilbert’s 16th problem is remained unsolved since Hilbert \textsuperscript{[1]} proposed the 23 mathematical problems at the Second International Congress of Mathematics in 1990. Recently, a modern version of the second part of the 16th problem was formulated by Smale \textsuperscript{[2]}, chosen as one of the 18 challenging mathematical problems for the 21st century. To be more specific, consider the following planar system:

\[
\begin{align*}
\frac{dx}{dt} &= P_n(x, y), \\
\frac{dy}{dt} &= Q_n(x, y),
\end{align*}
\] (1.1)

where \( P_n(x, y) \) and \( Q_n(x, y) \) represent \( n^{th} \)-degree polynomials of \( x \) and \( y \). The second part of Hilbert’s 16th problem is to find the upper bound \( H(n) \leq n^q \) on the number of limit cycles that the system can have, where \( q \) is a universal constant, and \( H(n) \) is called Hilbert number. In early 90’s of the last century, Ilyashenko \textsuperscript{[3]} and Écalle \textsuperscript{[4]} proved the finiteness theorem pioneered by Dulac, for given planar polynomial vector fields. In general

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the finiteness problem has not been solved even for quadratic systems. A recent survey article [5] (and more references therein) has comprehensively discussed this problem and reported the recent progress.

If the problem is restricted to the neighborhood of isolated fixed points, then the question is reduced to studying degenerate Hopf bifurcations, which give rise to fine focus points. In the past six decades, many researchers have considered the local problem and obtained many results (e.g., see [6–12]). In the last 20 years, much progress on finite cyclicity near a fine focus point or a homoclinic loop has been achieved. Roughly speaking, the so-called finite cyclicity means that at most a finite number of limit cycles can exist in some neighborhood of focus points or homoclinic loop under small perturbations on the system’s parameters.

In this paper, we particularly consider bifurcation of limit cycles in quadratic systems. Early results can be found in a survey article by Ye [13]. Some recent progress has been reported in a number of papers (e.g., see [14, 15]). For general quadratic system (1.1) \( n = 2 \), in 1952, Bautin [6] proved that there exist 3 small limit cycles around a fine focus point or a center. After 30 years, until the end of 1970’s, concrete examples were given to show that general quadratic systems can have 4 limit cycles [16, 17], around two foci with (3, 1) configuration. Since then, many researchers have paid attention to integrable quadratic systems, and a number of results have been obtained. A question was naturally raised: Can near-integrable quadratic systems have 4 limit cycles? A quadratic system is called near-integrable if it is a perturbation of a quadratic integrable system by quadratic polynomials. On one hand, it is reasonable to believe that the answer should be positive since general quadratic systems have at least 4 limit cycles; while on the other hand, near-integrable quadratic systems have limitations on their system parameters and thus it is more difficulty to find 4 limit cycles in such systems. In fact, this is still an open problem after another 30 years since the finding of 4 limit cycles in general quadratic systems.

The study of bifurcation of limit cycles for near-integrable systems is related to the so called weak Hilbert’s 16th problem [18], which is transformed to finding the maximal number of isolated zeros of the Abelian integral or Melnikov function:

\[
M(h, \delta) = \oint_{H(x,y)=h} Q_n \, dx - P_n \, dy, \quad (1.2)
\]

where \( H(x,y) \), \( P_n \) and \( Q_n \) are all real polynomials of \( x \) and \( y \) with \( \deg H = n + 1 \), and \( \max\{\deg P_n, \deg Q_n\} \leq n \). The weak Hilbert’s 16th problem is a very important problem, closely related to the maximal number of limit cycles of the following near-Hamiltonian system [19]:

\[
\frac{dx}{dt} = \frac{\partial H(x,y)}{\partial y} + \varepsilon p_n(x,y), \quad \frac{dy}{dt} = -\frac{\partial H(x,y)}{\partial x} + \varepsilon q_n(x,y), \quad (1.3)
\]

where \( H(x,y) \), \( p_n(x,y) \) and \( q_n(x,y) \) are polynomials of \( x \) and \( y \), and \( 0 < \varepsilon \ll 1 \) is a small perturbation.

General quadratic systems with one center have been classified by Žoladek [20] using a complex analysis on the condition of the center, as four systems: \( Q_{3}^{LV} \) – the Lotka-Volterra
system; $Q_3^H$ – Hamiltonian system; $Q_3^R$ – reversible system; and $Q_4$ – codimension-4 system. In 1994, Horozov and Iliev [21] proved that in quadratic perturbation of generic quadratic Hamiltonian vector fields with one center and three saddle points there can appear at most two limit cycles, and this bound is exact. Later, Gavrilov [22] extended Horozov and Iliev’s method to give a fairly complete analysis on quadratic Hamiltonian systems with quadratic perturbations. Quadratic Hamiltonian systems, with at most four singularities, can be classified as three cases [22]: (i) one center and three saddle points; (ii) one center and one saddle point; and (iii) two centers and two saddle points. In [22], Gavrilov showed that like case (i), cases (ii) and (iii) can also have at most two limit cycles. Therefore, generic quadratic Hamiltonian systems with quadratic perturbations can have maximal two limit cycles, and this case has been completely solved.

For the $Q_3^R$ reversible system, there have been many results published. For example, Dumortier et al. [23] studied a case of $Q_3^R$ system with two centers and two unbounded heteroclinic loops, and presented a complete analysis of quadratic 3-parameter unfolding. It was proved that 3 is the maximal number of limit cycles surrounding a single focus, and only the (1, 1)-configuration can occur in case of simultaneous nests of limit cycles. That is, 3 is the maximal number of limit cycles for the system they studied [23]. Later, Peng [24] considered a similar case with a homoclinic loop and showed that 2 is the maximal number of limit cycles which can bifurcate from the system. Around the same time, Yü and Li [25] investigated a similar case as Peng considered but with a varied parameter in a certain interval, and obtained the same conclusion as Peng’s. Later, Iliev et al. [26] re-investigated the same case but for the varied parameter in a different interval (which yields two centers) and got the same conclusion as that of [23], i.e., 3 is the maximal number of limit cycles which can be obtained from this case. Recently, Li and Llibre [27] considered a different case of $Q_3^R$ system which can exhibit the configurations of limit cycles: (0, 0), (1, 0), (1, 1) and (1, 2). Again, no 4 limit cycles were found. In order to explain why the above authors did not find 4 limit cycles from the $Q_3^R$ reversible system, consider the $Q_3^R$ system with quadratic perturbations, which can be described by

$$
\begin{align*}
\dot{x} &= -y + ax^2 + by^2 + \varepsilon (\mu_1 x + \mu_2 xy), \\
\dot{y} &= x (1 + cy) + \varepsilon \mu_3 x^2,
\end{align*}
$$

(1.4)

where $a, b, c$ are real parameters, $\mu_i$, $i = 1, 2, 3$ are real perturbation parameters, and $0 < \varepsilon \ll 1$. When $\varepsilon = 0$, system (1.4)$_{\varepsilon=0}$ is a reversible integrable system. It has been noted that in all the cases considered in [23-26], the parameters $a$ and $c$ were chosen as $a = -3$, $c = -2$, but with $b = 1$ in [23]; $b = -1$ in [24], $b \in (-\infty, -1) \cup (-1, 0)$ in [25], and $b \in (0, 2)$ in [26]. In these papers, complete analysis on the perturbation parameters was carried out with the aid of Poincaré transformation and the Picard-Fuchs equation, but it needed to fix all (or most of) the parameters $a$, $b$ and $c$. This way it may miss opportunity to find more limit cycles, such as possible existence of 4 limit cycles. As a matter of fact, for the cases considered in [25-26], a simple scaling on the parameter $b$ ($b \neq 0$) can be used to eliminate $b$. So, suppose the non-perturbed system (1.4)$_{\varepsilon=0}$ has two free parameters and let us consider the 2-dimensional parameter plane. Then, all the cases studied in the above
mentioned articles are special cases, represented by just a point or a line segment in the 2-dimensional parameter plane (see more details in Section 2). It has been noted that a different method was used in [27] with Melnikov function up to second order, but no more limit cycles were found.

It should be mentioned that Zhang [28] has proved that the possible cycle distributions in general quadratic systems with two foci must be \((0, 1)\)-distribution or \((1, i)\)-distribution, \(i = 0, 1, 2, 3, \ldots\). So far, no results have been obtained for \(i \geq 4\). This result also rules out the possibility of \((2, 2)\)-distribution. It is conjectured that at most 3 limit cycles can exist around one focus point. The problem of bifurcation of 3 limit cycles near an isolated homoclinic loop is still open.

In this paper, we turn to a different angle to consider bifurcation of limit cycles in quadratic near-integrable systems with two centers. We shall leave more free parameters in the integrable systems, so that we will have more chances to find more limit cycles. The basic idea is as follows: we first consider bifurcation of multiple limit cycles from Hopf singularity, which does not need to fix any parameters, and use expansion of Melnikov function near centers to get such limit cycles as many as possible. This leads to determination of a maximal number of parameters. Then, for the remaining undetermined parameters, we compute the global Melnikov function to look for possible large limit cycles. Indeed, although, due to the complex integrating factor in the analysis, we are not able to give a complete analysis for classifying the perturbation unfolding, we do get a positive answer to the open question of existence of 4 limit cycles in quadratic near-integrable systems. In particular, we will show that perturbing a reversible, integrable quadratic system with two centers can have at least 4 limit cycles, with \((3, 1)\) distribution, bifurcating from the two centers under quadratic perturbations.

The rest of paper is organized as follows. In Section 2, we give a different classification in real domain for quadratic systems with one center, and compare it with that given by Žoladek [20]. Also, we use our classification to present a simple summary on some of the existing results for the reversible near-integrable system. Section 3 is devoted to the analysis on bifurcation of small limit cycles from Hopf singularity. In Section 4, we show how to find large limit cycles bifurcating from closed orbits to obtain a total of 4 limit cycles. Finally, conclusion is drawn in Section 5.

2 Classification of generic quadratic systems with at least one center

In this section, we give a different classification in real domain for quadratic systems with a center, which is consistent with the Hamiltonian systems considered in [21] [22]. We start from the following general quadratic system:
\[ \frac{dz_1}{dt} = c_{100} + c_{110} z_1 + c_{101} z_2 + c_{120} z_1^2 + c_{111} z_1 z_2 + c_{102} z_2^2, \]
\[ \frac{dz_2}{dt} = c_{200} + c_{210} z_1 + c_{201} z_2 + c_{220} z_1^2 + c_{211} z_1 z_2 + c_{202} z_2^2, \]

where \(c_{ijk}\)'s are real constant parameters. It is easy to show that this system has at most four singularities, or more precisely, it can have 0, 2 or 4 singularities in real domain. In order for system (2.1) to have limit cycles, the system must have some singularity. In this paper, we assume that system (2.1) has at least two singularities. Without loss of generality, we may assume that one singular point is located at the origin \((0, 0)\), which implies \(c_{100} = c_{200} = 0\), and the other at \((p, q)\) \((p^2 + q^2 \neq 0)\). Further assume the origin is a linear center. Then introducing a series of linear transformations, parameter rescaling and time rescaling to system (2.1) yields the following general quadratic system:

\[ \frac{dx}{dt} = y + a_1 x y + a_2 y^2, \]
\[ \frac{dy}{dt} = -x + x^2 + a_3 x y + a_4 y^2, \]

which has a linear center at the origin \((0, 0)\) and another singularity at \((1, 0)\).

In order to have the origin of system (2.1) being a center, we may calculate the focus values of system (2.1) and find four cases under which \((0, 0)\) is a center, listed in the following theorem (here we use Žoladek’s notation in our classification).

**Theorem 1.1** The origin of (2.1) is a center if and only if one of the following conditions is satisfied:

\(Q^R_3\) – Reversible system: \(a_3 = a_2 = 0\), under which system (2.1) becomes

\[ \frac{dx}{dt} = y + a_1 x y, \]
\[ \frac{dy}{dt} = -x + x^2 + a_4 y^2, \]

with

\((1, 0)\) being a \(\begin{cases} \text{center} & \text{if } a_1 < -1, \\ \text{saddle point} & \text{if } a_1 > -1. \end{cases}\)

\(Q^H_3\) – Hamiltonian system: \(a_3 = a_1 + 2a_4 = 0\), under which system (2.1) is reduced to

\[ \frac{dx}{dt} = y + a_1 x y + a_2 y^2, \]
\[ \frac{dy}{dt} = -x + x^2 - \frac{1}{2}a_1 y^2, \]

with

\((1, 0)\) being a \(\begin{cases} \text{center} & \text{if } a_1 < -1, \\ \text{saddle point} & \text{if } a_1 > -1. \end{cases}\)
$Q_3^{LV}$ – Lokta-Volterra system: $a_2 = 1 + a_4 = 0$, under which system (??) becomes

$$\begin{align*}
\frac{dx}{dt} &= y + a_1 x y, \\
\frac{dy}{dt} &= -x + x^2 + a_3 x y - y^2,
\end{align*}$$

(2.5)

with

$$(1, 0) \text{ being a } \left\{ \begin{array}{ll}
\text{focus} & \text{if } a_1 < -(1 + \frac{1}{4} a_3^2), \\
\text{node} & \text{if } -(1 + \frac{1}{4} a_3^2) < a_1 < -1, \\
\text{saddle point} & \text{if } a_1 > -1.
\end{array} \right.$$

$Q_4$ – Codimension-4 system:

$$a_3 - 5 a_2 = a_1 - (5 + 3 a_4) = a_4 + 2(1 + a_2^2) = 0,$$ 

(2.6)

under which system (??) can be rewritten as

$$\begin{align*}
\frac{dx}{dt} &= y - (1 + 6 a_2^2) x y + a_2 y^2, \\
\frac{dy}{dt} &= -x + x^2 + 5 a_2 x y - 2 (1 + a_2^2) y^2,
\end{align*}$$

(2.7)

with $(1, 0)$ being a node for $a_2 \neq 0$.

**Remark 1.2.** There is one more case found from the above process, defined by the following conditions:

$$a_3 - 5 a_2 = a_1 - (5 + 3 a_4) = 3 (a_4 + 2) (a_4 + 1)^2 - (5 a_4 + 6) a_2^2 = 0.$$

We will show later in this section, when we compare our above real classification with the complex classification given by Žoládek [20], that the case defined by (??) actually belongs to the $Q_3^R$-reversible system.

**Proof.** Necessity is easy to be verified by computing the focus values of system (??) associated with the origin. Some focus values will not equal zero if the condition is not satisfied.

For sufficiency, we find an integrating factor for each case when the condition holds. For the $Q_3^H$-Hamiltonian system (??), we know that the integrating factor is 1, and the Hamiltonian is given by

$$H(x, y) = \frac{1}{2} (x^2 + y^2) - \frac{1}{3} x^3 + \frac{1}{2} a_1 x y^2 + \frac{1}{3} a_2 y^3,$$

(2.9)

which is exactly the same as that given in [21] [22].

For the $Q_3^R$-reversible system (??), the integrating factor is

$$\gamma = |1 + a_1 x|^{-\frac{a_4 + 2 a_4}{a_1}},$$

(2.10)
and the first integral of the system is given by

\[
F(x, y) = \frac{1}{2} \text{sign}(1 + a_1 x) \left| 1 + a_1 x \right|^\frac{2a_1}{a_1} \left[ y^2 + \frac{(1 + a_1 - a_4)(1 + 2a_4 x)}{a_4(a_1 - a_4)(a_1 - 2a_4)} - \frac{x^2}{a_1 - a_4} \right].
\] (2.11)

For the \(Q^L_{LV}\) - Lotka-Volterra system (??), we find the integrating factor to be

\[
\gamma = |g(x, y)|^{-1}, \quad \text{where } g(x, y) = (1 + a_1 x) \left[ (x - 1)^2 + a_3 (x - 1) y - (1 + a_1) y^2 \right].
\] (2.12)

and the first integral of the system is

\[
F(x, y) = \begin{cases} 
- \frac{\text{sign}(g(x, y))}{2a_1(1 + a_1)} \left\{ 2 \ln |1 + a_1 x| + a_1 \ln \left| (1 + a_1) y^2 - a_3 y (x - 1) - (x - 1)^2 \right| 
+ \frac{2a_1 a_3 (x - 1)}{\sqrt{a_3^2 + 4(1 + a_1)}} \sqrt{(x - 1)^2} \tanh^{-1} \left[ \frac{a_3 (x - 1) - 2(1 + a_1) y}{\sqrt{a_3^2 + 4(1 + a_1)}} (x - 1)^2 \right], 
\end{cases}
\] (2.13)

when \(a_3^2 + 4(1 + a_1) > 0\),

\[
F(x, y) = \begin{cases} 
- \frac{\text{sign}(1 + a_1 x)}{2a_1(1 + a_1)} \left\{ 2 \ln |1 + a_1 x| + a_1 \ln \left| (1 + a_1) y^2 - a_3 y (x - 1) - (x - 1)^2 \right| 
- \frac{2a_1 a_3 (x - 1)}{\sqrt{-a_3^2 - 4(1 + a_1)}} \sqrt{(x - 1)^2} \tanh^{-1} \left[ \frac{a_3 (x - 1) - 2(1 + a_1) y}{\sqrt{-a_3^2 - 4(1 + a_1)}} (x - 1)^2 \right], 
\end{cases}
\] (2.13)

when \(a_3^2 + 4(1 + a_1) < 0\).

Finally, for the \(Q^4\) - codimension-4 system (??), we have

\[
\gamma = |g(x, y)|^{-5/2}, \quad \text{where } g(x, y) = 1 - 2(1 + 2a_2^2) x - 2a_2 y + (1 + 4a_2^2)(x + a_2 y)^2.
\] (2.14)

and the first integral of the system is equal to

\[
F(x, y) = \frac{\text{sign}(g(x, y))}{12a_2^5} |g(x, y)|^{-3/2} f(x, y).
\] (2.15)

where

\[
f(x, y) = -(1 + a_2^2) + 3(x + a_2 y + 2a_2 x) \left[ 1 + a_2^2 - (1 + 3a_2^2)(x + a_2 y) \right]
+ (1 + 3a_2^2)(1 + 4a_2^2)(x + a_2 y)^3.
\] (2.16)

The proof is complete. \(\square\)

Note that among the four classifications of the integrable system (??), the first three classified systems (??), (??) and (??) have two free parameters, while the last system (??) has only one free parameter.

Remark 1.3. We now show that our classification in Theorem 1.1 is equivalent to that given by Žoladěk [20]. The general quadratic system considered in [20] is given in the complex form:

\[
\frac{dz}{dt} = (i + \lambda) z + A z^2 + B z \bar{z} + C \bar{z}^2.
\] (2.17)
where \( z = x + iy \), and \( A, B \) and \( C \) are complex coefficients. It has been shown in \cite{20} that the point \( z = 0 \) is a center if and only if one of the following conditions is fulfilled:

\[
\begin{align*}
Q_3^{LV} : & \quad \lambda = B = 0, \\
Q_3^H : & \quad \lambda = 2A + \overline{B} = 0, \\
Q_3^R : & \quad \lambda = \text{Im}(AB) = \text{Im}(B^3C) = \text{Im}(A^3C) = 0, \\
Q_4 : & \quad \lambda = A - 2\overline{B} = |C| - |B| = 0.
\end{align*}
\]

In the following, we first use real differential equation to give a brief proof (different from \( \dot{Z}ol\acute{a}dek's \) \cite{20}), and then show that our classification is equivalent to \( \dot{Z}ol\acute{a}dek's \) when system \((??)\) is assumed to have a non-zero singularity. To prove this, let \( A = A_1 + iA_2, \quad B = B_1 + iB_2, \quad C = C_1 + iC_2, \quad (i^2 = -1) \), and then rewrite the complex equation \((??)\) in the real form:

\[
\begin{align*}
\frac{dx}{dt} &= \lambda x + y + (A_1 + B_1 + C_1)x^2 + 2(A_2 - C_2)xy - (A_1 - B_1 + C_1)y^2, \\
\frac{dy}{dt} &= -x + \lambda y - (A_2 + B_2 + C_2)x^2 + 2(A_1 - C_1)xy + (A_2 - B_2 + C_2)y^2,
\end{align*}
\]

where \( y \to -y \) has been used. Letting \( \lambda = 0 \) yields the focus value \( v_0 = 0 \). Then, it is easy to find the first focus value (or the first Lyapunov constant) as

\[
v_1 = -A_1B_2 - B_1A_2 = -\text{Im}(AB).
\]

Letting \( v_1 = 0 \) results in \( \text{Im}(AB) = 0 \), which gives

\[
B_2 = -\frac{B_1A_2}{A_1}, \quad \text{under the assumption of} \quad A_1 \neq 0.
\]

(The degenerate case \( A_1 = 0 \) can be similarly analyzed and the details are omitted here.) Then, we apply our Maple program (e.g., see \cite{29}) to system \((??)\), with the conditions \( \lambda = 0 \) and \((??)\), to obtain

\[
\begin{align*}
v_2 &= \frac{-f(A_1 - 2B_1)}{3A_1^3}, \\
v_3 &= \frac{-f_3}{216A_1^3}, \\
v_4 &= \frac{-f_4}{9720A_1^7}, \\
v_5 &= \frac{-f_5}{466560A_1^{11}}, \\
\end{align*}
\]

where

\[
f = B_1(2A_1 + B_1)(C_2A_1^3 + 3C_1A_2A_1^2 - 3A_2^2C_2A_1 - C_1A_2^3),
\]

and \( f_3, f_4, \) etc. are polynomials of \( A_1, A_2, C_1, C_2 \) and \( B_1 \). Letting \( f = 0 \), i.e.,

\[
B_1 = 0 \quad \text{or} \quad 2A_1 + B_1 = 0 \quad \text{or} \quad C_2A_1^3 + 3C_1A_2A_1^2 - 3A_2^2C_2A_1 - C_1A_2^3 = \text{Im}(A^3C) = 0
\]

yields \( v_2 = v_3 = \cdots = 0 \).
Indeed, $B_1 = 0$ implies $B_2 = 0$ due to the condition (??), and so $B = 0$. Thus, we obtain \( \lambda = B = 0 \), corresponding to the $Q_L^V$ case.

For the condition $2A_1 + B_1 = 0$, it follows from (??) that $2A_2 - B_2 = 0$, i.e., $2A + \bar{B} = 0$, which plus the condition $\lambda = 0$ gives the $Q_H^L$ case.

The third condition $\text{Im}(A^3C) = 0$, with $\lambda = 0$ and $\text{Im}(AB) = 0$, corresponds to the $Q_3^R$ case. Further, it is easy to show that under the condition $\text{Im}(AB) = 0$, $\text{Im}(A^3C) = 0$ and $\text{Im}(\bar{B}^3C) = 0$ are equivalent. Thus, the conditions $\lambda = \text{Im}(AB) = \text{Im}(\bar{B}^3C) = 0$ also applicable for this case. So for this case, either $\text{Im}(A^3C) = 0$ or $\text{Im}(\bar{B}^3C) = 0$ is needed, but not both of them. In the following, we show one more case to join this case, leading to both the two conditions being needed.

Note that there is one more condition $A_1 = 2B_1$ which renders $v_2 = 0$. Letting $A_1 = 2B_1$, and so $A_2 = -2B_2$ (see (??)), implying that $A - 2\bar{B} = 0$. Under the condition $A = 2\bar{B}$, $v_1 = v_2 = 0$, and the other focus values become

\[
\begin{align*}
v_3 &= \frac{25}{8} (C_1^2 + C_2^2 - B_1^2 - B_2^2)(C_2 B_1^3 - 3C_1 B_1^2 B_2 - 3C_2 B_1 B_2^2 + C_1 B_2^3), \\
v_4 &= \frac{v_3}{45} [45B_1^2 + 585B_2^2 + 60(B_1C_1 + B_2C_2) - 196(C_1^2 + C_2^2)], \\
v_5 &= \frac{v_3}{6480} [648(7B_1^4 + 124B_1^2 B_2^2 + 1557B_2^4) - 3(961B_1^2 C_1^2 - 7680B_1B_2C_1C_2 + 202345B_2^2 C_2^2) \\
&\quad + 576B_1 C_1(106B_1^2 + 307B_2^2) + 288B_2 C_2(371B_1^2 + 773B_2^2) \\
&\quad - 3(4801B_1^2 C_2^2 + 206185B_2^2 C_1^2) - 80688(C_1^2 + C_2^2)(B_1C_1 + B_2C_2) \\
&\quad + 86144(C_1^2 + C_2^2)^2],
\end{align*}
\]

Hence, under the conditions $\lambda = A - 2\bar{B} = 0$, there are two possibilities such that $v_3 = v_4 = \cdots = 0$. The first possibility is

\[
C_1^2 + C_2^2 - B_1^2 - B_2^2, \quad \text{i.e., } |C| - |B| = 0,
\]

which is one of the conditions given for the $Q_4$ case (see (??)).

The second possibility is given by the condition:

\[
C_2 B_1^3 - 3C_1 B_1^2 B_2 - 3C_2 B_1 B_2^2 + C_1 B_2^3 = \text{Im}(\bar{B}^3C) = \frac{1}{8} \text{Im}(A^3C) = 0, \text{lb26} \quad (2.22)
\]
due to $A = 2B$. Since these conditions can be included in the conditions $\lambda = \text{Im}(AB) = \text{Im}(\bar{B}^3C) = \text{Im}(A^3C) = 0$, this possibility belongs to the $Q_3^R$ case.

The remaining task is to show that the conditions classified in (??) are sufficient. This can be done by finding an integrating factor for each case. For brevity, we only list these
Then, let

$$\lambda = \frac{2A_1 + B_1}{A_1 - C_1}$$

for $Q^R_5$, considering the cubic polynomial below (while the lengthy expressions of the first integrals are omitted):

$$\gamma = \left\{ \begin{array}{ll}
|1 + 4(A_2 x - A_1 y) + 4(A_1 C_2 + A_2 C_1 - 2A_1 A_2) xy + [(A_1 + C_1)(A_1 - 3C_1) + (A_2 + C_2)(5A_2 - 3C_2)] x^2 \\
+ [(A_2 + C_2)(A_2 - 3C_2) + (A_1 + C_1)(5A_1 - 3C_1)] y^2 \\
+ 2(A_1^2 + A_2^2 - C_1^2 - C_2^2) [(A_2 + C_2)x^3 - (A_1 + C_1)y^3 - (A_1 - 3C_1)x^2 y + (A_2 - 3C_2)xy^2]^{-1}, & \text{for } Q^L_5, lb27 (2.23) \\
1, & \text{for } Q^H_5, \\
|1 - 2(A_1 - C_1)y|^{-\frac{2A_1 + B_1}{A_1 - C_1}}, & \text{for } Q^R_5, \\
|1 - 4(B_2 x + B_1 y) + 2(B_1^2 + B_2^2)(x^2 + y^2) + 2(B_1 C_1 + B_2 C_2)(x^2 - y^2) + 4(B_1 C_2 - B_2 C_1)xy|^{-5/2}, & \text{for } Q_4.
\end{array} \right.$$  

For the integrating factors of degenerate cases (e.g., $A_1 - C_1 = 0$), one can easily find them.

Next, compare the classification listed in (2.20) with ours given in Theorem 1.1. First, consider the $Q^L_5$ case. Letting $\lambda = B_1 = B_2 = 0$ in (2.20) yields

$$\frac{dx}{dt} = y + (A_1 + C_1)x^2 + 2(A_2 - C_2)xy - (A_1 + C_1)y^2, \quad lb28$$

$$\frac{dy}{dt} = -x - (A_2 + C_2)x^2 + 2(A_1 - C_1)xy + (A_2 + C_2)y^2.$$  

Then, let

$$k = \tan(\theta), \quad \text{and so } \sin(\theta) = \frac{k}{\sqrt{1 + k^2}}, \quad \cos(\theta) = \frac{1}{\sqrt{1 + k^2}}, lb29 (2.25)$$

where $k$ is solved from the following cubic polynomial:

$$P_1(k) = (A_2 + C_2)k^3 + (A_1 - 3C_1)k^2 + (A_2 - 3C_2)k + A_1 + C_1 = 0.lb30 (2.26)$$

This cubic polynomial at least has one real solution for $k$, which gives the slope of the line on which a second fixed point is located. $k = 0$ if $A_1 + C_1 = 0$, otherwise, $k \neq 0$. Let $k$ be a real root of $P_1(k)$, i.e., $P_1(k) = 0$.

Further, introducing the linear transformation (rotation):

$$x = \cos(\theta) u - \sin(\theta)v, \quad y = \sin(\theta) u + \cos(\theta)v, lb31 (2.27)$$

into (2.20) yields

$$\frac{dx}{dt} = y + m_{120}x^2 + m_{111}xy + m_{102}y^2, \quad lb32$$

$$\frac{dy}{dt} = -x + m_{220}x^2 + m_{211}xy + m_{202}y^2,$$  

where $m_{ij}$ are determined by the coefficients of the cubic polynomial $P_1(k)$.
where
\[ m_{120} = -m_{102} = (1 + \overline{k}^2)^{-3/2} P_1(\overline{k}) = 0, \]
\[ m_{220} = -m_{202} = (1 + \overline{k}^2)^{-3/2} \left[ (A_1 + C_1) \overline{k}^3 - (A_2 - 3 C_2) \overline{k}^2 + (A_1 - 3 C_1) \overline{k} - A_2 - C_2 \right], \]
\[ m_{111} = -2 (1 + \overline{k}^2)^{-3/2} \left[ (A_1 - C_1) \overline{k}^3 - (A_2 + 3 C_2) \overline{k}^2 + (A_1 + 3 C_1) \overline{k} - A_2 + C_2 \right], \]
\[ m_{211} = 2 (1 + \overline{k}^2)^{-3/2} \left[ (A_2 - C_2) \overline{k}^3 + (A_1 + 3 C_1) \overline{k}^2 + (A_2 + 3 C_2) \overline{k} + A_1 - C_1 \right]. \]

Suppose \( m_{220} \neq 0 \). Then, introducing \( \overline{x} = m_{220} x, \overline{y} = m_{220} y \) into (2) results in
\[
\frac{d\overline{x}}{dt} = \overline{y} + \frac{m_{111}}{m_{220}} \overline{x} \overline{y},
\]
\[
\frac{d\overline{y}}{dt} = -\overline{x} + \overline{x}^2 + \frac{m_{211}}{m_{220}} x y - \overline{y}^2, \tag{2.29}
\]
which is identical to (2) as long as letting \( a_1 = \frac{m_{111}}{m_{220}} \) and \( a_3 = \frac{m_{211}}{m_{220}} \). This shows that the four parameters \( A_1, A_2, C_1 \) and \( C_2 \) are not independent. Thus, alternatively, we may simply take \( \overline{k} = 0 \) (which renders the second singularity of (2) on the x-axis), yielding \( C_1 = -A_1 \). Thus, (2) becomes
\[
\frac{dx}{dt} = y + 2 (A_2 - C_2) x y,
\]
\[
\frac{dy}{dt} = -x - (A_2 + C_2) x^2 + 4 A_1 x y + (A_2 + C_2) y^2.
\]

Suppose \( A_2 + C_2 \neq 0 \). Introducing \( \overline{x} = -(A_2 + C_2) x, \overline{y} = -(A_2 + C_2) y \) into the above equations we obtain
\[
\frac{d\overline{x}}{dt} = \overline{y} - \frac{2(A_2-C_2)}{A_2+C_2} \overline{x} \overline{y},
\]
\[
\frac{d\overline{y}}{dt} = -\overline{x} + \overline{x}^2 - \frac{4 A_1}{A_2+C_2} \overline{x} \overline{y} - \overline{y}^2, \tag{2.30}
\]
which is identical to (2) if letting \( a_1 = -\frac{2(A_2-C_2)}{A_2+C_2} \) and \( a_3 = \frac{4 A_1}{A_2+C_2} \). In the following, we will use this simple approach for other cases.

For the \( Q_3^A \) case, substituting \( \lambda = 0, B_1 = -2 A_1 \) and \( B_2 = 2 A_2 \) into system (2) results in
\[
\frac{dx}{dt} = y - (A_1 - C_1) x^2 + 2 (A_2 - C_2) x y - (3 A_1 + C_1) y^2,
\]
\[
\frac{dy}{dt} = -x - (3 A_2 + C_2) x^2 + 2 (A_1 - C_1) x y - (A_2 - C_2) y^2.
\]
Further, taking \( C_1 = A_1 \) in the above equations gives another singularity on the x-axis, and introducing \( \overline{x} = -(3 A_2 + C_2) x, \overline{y} = -(3 A_2 + C_2) y \) into the resulting equations yields
\[
\frac{d\overline{x}}{dt} = \overline{y} - \frac{2(A_2-C_2)}{3 A_2+C_2} \overline{x} \overline{y} + \frac{4 A_1}{3 A_2+C_2} \overline{y}^2, \tag{2.31}
\]
\[
\frac{d\overline{y}}{dt} = -\overline{x} + \overline{x}^2 + \frac{A_2-C_2}{3 A_2+C_2} \overline{y}^2,
\]
which is identical to (??) if we set \( a_1 = \frac{-2(A_2-C_2)}{3A_2+C_2} \) and \( a_2 = \frac{4A_4}{3A_2+C_2} \).

For the \( Q_3^R \) reversible case, it follows from [20] that all the coefficients \( A, B \) and \( C \) are real, and thus we obtain the following real form from the complex system (??)

\[
\begin{align*}
\frac{dx}{dt} &= -y + a x^2 + b y^2, \\
\frac{dy}{dt} &= x + c x y,
\end{align*}
\]

(2.32)

where

\[
a = A_1 + B_1 + C_1, \quad b = B_1 - A_1 - C_1, \quad c = 2A_1 - 2C_1.
\]

Suppose \( b \neq 0 \). Then, introducing \( \bar{x} = b y, \ \bar{y} = b x \) into (??) results in

\[
\begin{align*}
\frac{d\bar{x}}{dt} &= \bar{y} + \frac{c}{b} \bar{x} \bar{y}, \\
\frac{d\bar{y}}{dt} &= -\bar{x} + \bar{x}^2 + a \frac{\bar{y}}{b}^2,
\end{align*}
\]

(2.33)

which is identical to (??) if

\[
a_1 = \frac{c}{b} = \frac{2(A_1 - C_1)}{B_1 - A_1 - C_1} \quad \text{and} \quad a_4 = \frac{a}{b} = \frac{A_1 + B_1 + C_1}{B_1 - A_1 - C_1}.
\]

For the last \( Q_4 \) case, under the condition \( \lambda = A - 2\bar{B} = 0 \), by setting \( C_1 = -3B_1 \) (which renders a non-zero singularity on the \( x \)-axis) in (??) we obtain

\[
\begin{align*}
\frac{dx}{dt} &= y - 2(2B_2 + C_2) xy + 2B_1 y^2, \\
\frac{dy}{dt} &= -x + (B_2 - C_2)x^2 + 10B_1 xy - (3B_2 - C_2)y^2,
\end{align*}
\]

Suppose \( B_2 - C_2 \neq 0 \). Then, introducing \( \bar{x} = (B_2 - C_2)x, \ \bar{y} = (B_2 - C_2)y \) into the above equations yields

\[
\begin{align*}
\frac{d\bar{x}}{dt} &= \bar{y} - \frac{2(2B_2+C_2)}{B_2-C_2} \bar{x} \bar{y} + \frac{2B_1}{B_2-C_2} \bar{y}^2, \\
\frac{d\bar{y}}{dt} &= -\bar{x} + \bar{x}^2 + \frac{10B_1}{B_2-C_2} \bar{x} \bar{y} - \frac{3B_2-C_2}{B_2-C_2} \bar{y}^2,
\end{align*}
\]

(2.34)

Comparing the coefficients of the above system (??) with our system (??) results in

\[
\begin{align*}
a_1 &= -\frac{2(2B_2+C_2)}{B_2-C_2}, \quad a_2 = \frac{2B_1}{B_2-C_2}, \quad a_3 = \frac{10B_1}{B_2-C_2}, \quad a_4 = -\frac{3B_2-C_2}{B_2-C_2},
\end{align*}
\]

(2.35)

which in turn implies that \( a_3 - 5a_2 = a_1 - (5 + 3a_4) = 0 \), and

\[
a_4 + 2(a_2^2) = \frac{8B_1^2+C_2^2-B_2^2}{(B_2-C_2)^2} = \frac{C_2^2+B_1^2-B_2^2}{(B_2-C_2)^2} = 0, \quad \text{for} \quad |C| - |B| = 0.
\]

The above conditions are the exact conditions given in (??) for the \( Q_4 \) case.
Finally, we turn to the conditions given in (??). It follows from (??) that
\[ 3 (a_4 + 2) (a_4 + 1)^2 - (5 a_4 + 6) a_2^2 = - \frac{4}{(b_2 - c_2)^3} (3 B_2^3 + 3 B_2^2 C_2 - C_1^2 B_2 - B_1^2 C_2). \]

On the other hand, under the condition \( C_1 = -3 B_1 \), the condition (??) for the second possibility becomes
\[
C_2 B_1^3 - 3 C_1 B_1^2 B_2 - 3 C_2 B_1^2 + C_1 B_2^3 = C_2 B_1^3 + C_1^2 B_1 B_2 - 3 C_2 B_1 B_2^2 - 3 B_1 B_2^3
\]
\[ = - B_1 (3 B_2^3 + 3 B_2^2 C_2 - C_1^2 B_2 - B_1^2 C_2) = 0, \]

which implies, by Eq. (??), \( 3 (a_4 + 2) (a_4 + 1)^2 - (5 a_4 + 6) a_2^2 = 0 \) for \( B_1 \neq 0 \). Hence, according to Žoladek’s classification (see (??)), this case should be included in the \( Q_3^R \) case. However, one can not prove this by directly using the conditions in (??) as well as that for the \( Q_3^R \) case (see Theorem 1.1). One must trace back to the original system coefficients.

In [20], Žoladek used Bautin’s system to verify his classification. Bautin’s system is described by [6]
\[
\begin{align*}
\frac{dx}{dt} &= \lambda_1 x - y + \lambda_3 x^2 + (2 \lambda_2 + \lambda_5) x y + \lambda_6 y^2, \\
\frac{dy}{dt} &= x + \lambda_1 y + \lambda_2 x^2 + (2 \lambda_3 + \lambda_4) x y - \lambda_2 y^2.
\end{align*}
\]

It is seen from (??) and (??) that Bautin’s system has only 6 parameters, while Žoladek’s system has 7 (in real domain) parameters. This indicates that Žoladek’s system has one redundant parameter. In fact, putting Bautin’s system in Žoladek’s complex form gives the following expressions:
\[
\lambda = \lambda_1, \quad A = \frac{1}{4} (\lambda_3 + \lambda_4 - \lambda_6 - i \lambda_5), \quad B = - \frac{1}{2} (\lambda_3 - \lambda_6),
\]
\[
C = \frac{1}{4} \left[ - (3 \lambda_3 + \lambda_4 + \lambda_6) + i (4 \lambda_2 + \lambda_5) \right].
\]

Then, applying the formulas given in (??) will immediately generate the centers conditions obtained by Bautin [6]. The above expressions clearly show that \( B_2 = 0 \). As a matter of factor, the integral factor for the system, corresponding to the second possibility, i.e., when \( \lambda = A - 2 \bar{B} = \text{Im}(\bar{B}^2 C) = 0 \), is given by
\[
\left| 1 + 2 \left[ \frac{C_1 (B_2^2 + B_4^2)}{B_1 (B_1^2 - 3 B_2^2)} - 2 \right] (B_2 x + B_1 y) \right|^2 \frac{5 B_4 (B_1^2 - 3 B_2^2)}{C_1 (B_1^2 + B_4^2) - 2 B_4 (B_1^2 - 3 B_2^2)}.
\]

For \( B_2 = 0 \), the above expression is reduced to
\[
\left| 1 - 2 \left( 2 B_1 - C_1 \right) y \right|^2 \frac{5 B_4}{C_1 (A_1 - C_1)} = \left| 1 - 2 \left( A_1 - C_1 \right) y \right|^2 \frac{2 A_1 + B_3}{A_1 - C_1} \quad \text{(due to} \quad A_1 = 2 B_1),
\]

which is the integrating factor for the \( Q_3^R \) system, as shown in (??).

Now we return to system (??). Among the four classifications, the Hamiltonian system \( (Q_3^H) \) has been completely studied in [21] [22]: the system can have maximal two limit cycles.
In this paper, we will concentrate on the $Q_3^R$-reversible case. Special cases for the reversible system have been investigated by a number of authors (e.g., see [23, 24, 25, 26, 27]). It is easy to see that system (2.2) is invariant under the mapping $(t, y) \to (-t, -y)$, where $a_1$ and $a_4$ can be considered as perturbation parameters. The singular point $(1, 0)$ of (2.2) is a center when $a_1 < -1$; but a saddle point when $a_1 > -1$. $a_1 = -1$ gives a degenerate singular point at $(1, 0)$. Further, it is easy to verify that when $(a_1 + 1)a_4 > 0$, there are no more singularity; while when $(a_1 + 1)a_4 < 0$, there exist additional two saddle points, given by

$$\left(-\frac{1}{a_1}, \pm \sqrt{-\frac{a_4(a_1+1)}{a_1a_4}}\right).$$

$a_4 = 0$ is a critical value, yielding the two additional saddle points at infinity: $(x^*, y^*) = (-\frac{1}{a_1}, \pm \infty)$. In summary, the distribution of singularity of the reversible system (2.2) has the following possibility (see Fig. 1, where 1C+1S stands for one center and one saddle point, similar meaning applies to 2C, 2C+2S and 1C+3S):

- Two centers when $a_1 < -1$ and $a_4 < 0$;
- Two centers and two saddle points when $a_1 < -1$ and $a_4 > 0$;
- One center and one saddle point when $a_1 > -1$ and $a_4 > 0$;
- One center and three saddle points when $a_1 > -1$ and $a_4 < 0$.

In this paper, we pay particular attention to $a_1 < -1$, $a_4 < 0$, for which system (2.2) has only two singularities at $(0, 0)$ and $(1, 0)$, both of them are centers.

By adding quadratic perturbations to system (2.2) we obtain the following perturbed quadratic system:

\[
\frac{dx}{dt} = y(1 + a_1 x) + \varepsilon P(x, y) \\
= y(1 + a_1 x) + \varepsilon (a_{10} x + a_{01} y + a_{20} x^2 + a_{11} x y + a_{02} y^2),
\]

\[
\frac{dy}{dt} = -x + x^2 + a_4 y^2 + \varepsilon Q(x, y) \\
= -x + x^2 + a_4 y^2 + \varepsilon (b_{10} x + b_{01} y + b_{20} x^2 + b_{11} x y + b_{02} y^2),
\]

where $0 < \varepsilon \ll 1$, $a_{ij}$’s and $b_{ij}$’s are perturbation parameters.

**Remark 1.4.** The special system considered in [23] is the system (2.2) with

$$a = -3, \quad c = -2, \quad b = 1.$$ 

This is equivalent to our system when $a_1 = -2$ and $a_4 = -3$ for which the system has only two centers at $(0, 0)$ and $(1, 0)$. Consider the $a_1$-$a_4$ parameter plane, as shown in Fig. 1. It can be seen that the case considered in [23] is just a point, $(a_1, a_4) = (-2, -3)$, in the parameter plane, marked by a blank circle in the third quadrant on the line $a_4 = \frac{3}{2} a_1$ (see Fig. 1).
The special system studied in [24] is the system (2.1) with
\[ a = -3, \quad c = -2, \quad b = -1. \]
This is equivalent to our system when \( a_1 = 2 \) and \( a_4 = 3 \), for which the system has one center at \((0,0)\) and one saddle point at \((1,0)\). Thus, this case considered in [24] is again a point, \((a_1, a_4) = (2, 3)\), in the \( a_1-a_4 \) parameter plane, marked by another blank circle in the first quadrant on the line \( a_4 = \frac{3}{2} a_1 \) (see Fig. 1).

The cases considered in [25, 26] correspond to the system (2.2) with \( a = -3, \quad c = -2, \) and \( b \in (-\infty, -1) \cup (-1, 0) \) in [25], and \( b \in (0, 2) \) in [26].

When \( \varepsilon = 0 \) in system (2.1), one can use the following transformation:
\[ x = \frac{\tilde{y}}{b}, \quad y = \frac{\tilde{x}}{b}, \]
to transform system (2.1)\(_{\varepsilon=0}\) to
\[
\begin{align*}
\frac{d\tilde{x}}{dt} &= \tilde{y} \left( 1 + \frac{c}{b} \tilde{x} \right), \quad (b \neq 0), \quad lb45 \\
\frac{d\tilde{y}}{dt} &= -\tilde{x} + \tilde{x}^2 + \frac{a}{b} \tilde{y}^2,
\end{align*}
\] (2.40)
which is our system (2.1) with
\[ a_1 = \frac{c}{b}, \quad a_4 = \frac{a}{b}, lb46 \]
Equation (2.2) yields
\[ a_4 = \frac{a}{c} a_1 \quad (b \neq 0), \quad lb47 \]
(2.42)
which represents a line in the \( a_1-a_4 \) parameter plane, passing through the origin with the slope \( \frac{a}{c} \). In particular, the parameter values: \( a = -3, \quad c = -2, \) \( b \in (-\infty, -1) \cup (-1, 0) \cup (0, 2) \), yielding \( a_1 = -\frac{2}{b} \) and \( a_4 = -\frac{3}{b} \), correspond to a part of the line, described by
\[ a_4 = \frac{3}{2} a_1 \quad \forall a_1 \in (-\infty, -1) \cup (0, \infty), lb48 \]
(2.43)
as shown in Fig. 1 where the dotted line for \( a_1 \in [-1, 0] \) is excluded from the studies [25, 26].

It should be noted that when \( a = -3, \quad c = -2, \) the point \((0, \frac{1}{b})\) is a saddle point if and only if
\[ 1 + \frac{c}{b} = 1 - \frac{2}{b} > 0 \quad \implies \quad b \in (-\infty, 0) \cup (2, +\infty). \]
Thus, the case considered in [25] has one center and one saddle point; while the case studied in [26] has two centers. But even these two studies together do not cover the whole line \( a_4 = \frac{3}{2} a_1 \) (the missing part is denoted by a dotted line segment in Fig. 1).

Another alternative form for a special case of our system (2.1) considered in [30] is described by
\[
\begin{align*}
\frac{d\tilde{x}}{dt} &= \tilde{y} \left[ 1 + 2 (1 - e) \left( \frac{x}{d} + \frac{1}{d} \right) \right], \quad lb49 \\
\frac{d\tilde{y}}{dt} &= x + d \tilde{x}^2 + e \tilde{y}^2,
\end{align*}
\] (2.44)
where $e$ and $d$ ($\neq 0$) are parameters. This system has a saddle point at the origin and a center at $(\frac{1}{d}, 0)$. Based on the two parameters, seven cases are classified. We can apply the following transformation:

\[
\begin{align*}
\bar{x} &= \frac{1}{d} (x - 1), \\
\bar{y} &= \frac{1}{d} y,
\end{align*}
\]

to system (2.38), yielding

\[
\begin{align*}
\frac{dx}{dt} &= y \left[ 1 + \frac{2(1 - e)}{d} x \right], \\
\frac{dy}{dt} &= -x + x^2 + \frac{e}{d} y^2,
\end{align*}
\]

which has a center at the origin and a saddle point at $(1, 0)$. Then, setting

\[
a_1 = \frac{2(1 - e)}{d}, \quad a_4 = \frac{e}{d},
\]

in system (2.38) leads to our system (2.39). Equation (2.47) denotes a line, given by

\[
a_4 = \frac{e}{2(1 - e)} a_1, \quad lb53
\]

in the $a_1$-$a_4$ parameter plane, passing through the origin with the slope $\frac{e}{2(1 - e)}$. However, it is easy to see that using our system (2.39) in analysis is simpler than using system (2.38). In fact, all the seven cases classified in [30] together denote a region in Fig. 1, see the shaded area in this figure. This area covers most of the region, defined by $a_1 > -1$. But the study given in [30] for the seven cases is restricted to local analysis on the bifurcation of limit cycles near a homoclinic loop, except the two lines (see Fig. 1):

\[
a_4 = \frac{a_1}{3}, \quad lb53
\]

which corresponds to the parameter value $e = \frac{2}{3}$, and

\[
a_4 = -\frac{1}{2} a_1, \quad lb54
\]

which corresponds to $e \to \pm \infty$. It has been shown [30] that except the above two lines, for the parameter values in the shaded area, system (2.39) can have at most 2 limit cycles near a homoclinic loop under quadratic perturbation.

Figure 1 shows the $a_1$-$a_4$ parameter plane associated with the reversible system (2.37), where the above mentioned case studies are indicated on the line $a_4 = \frac{3}{2} a_1$ as well as in the shaded area. More precisely, a complete global analysis given in [25], which includes the result in [23] as a special case, shows that corresponding to each point on the line segment $a_4 = \frac{3}{2} a_1 (a_1 > 0)$, the system has one center and one saddle point, and has maximal 2 limit cycles. In [30] it is shown for each point in the shaded area (except the two line segments $a_4 = a_1 (a_1 > -1)$ and $a_4 = -\frac{1}{2} a_1 (a_1 > 0)$), which contains the above line segment,
the system has one center and one (or three) saddle(s), and has maximal 2 limit cycles, but restricted to local analysis near one homoclinic loop. Similarly, a global analysis given in [26], which contains the result in [23] as a special case, proves that corresponding to each point on the line segment $a_4 = \frac{3}{2} a_1$ ($a_1 < -1$), the system has two centers, and exhibits maximal 3 limit cycles around one center. The technique of Poincaré transformation and Picard-Puchs equation, used for the above mentioned global analysis on parameter unfolding, seems not possible to be generalized to consider general situation for arbitrary points in the $a_1$-$a_4$ parameter plane. The two particular dash-dotted lines: $a_4 = \frac{1}{3} (a_1 - 5) \forall a_1 \in (-\infty, -1) \cup (-1, \infty)$, and $a_4 = \frac{1}{3} (6 a_1 + 5) \forall a_1 \in (-\infty, -1)$, as well as the five dark circles correspond to our results, presented in the next two sections. In particular, we will show that there exist 3 small limit cycles on the two dash-dotted lines, and at least 4 limit cycles for the parameter values marked by the five dark circles.

In the following, we will use the perturbed quadratic system (2.50) for our study on bifurcation of limit cycles. Without loss of generality, we may assume (e.g., see [23]) that $a_{01} = a_{20} = a_{11} = a_{02} = b_{10} = b_{20} = b_{02} = 0$. Thus, system (2.50) is reduced to

$$\begin{align*}
\frac{dx}{dt} &= y (1 + a_1 x) + \varepsilon a_{10} x, \\
\frac{dy}{dt} &= -x + x^2 + a_4 y^2 + \varepsilon (b_{01} y + b_{11} x y),
\end{align*}$$

(2.50)

where $a_1 < -1$ and $0 < \varepsilon \ll 1$. 

Figure 1: Case studies for the $Q^R_3$ reversible system.
3 Hopf bifurcation associated with the two centers

In this section, we study Hopf bifurcation of system (3.1) from two centers (0, 0) and (1, 0), leading to bifurcation of multiple limit cycles. The result is summarized in the following theorem.

**Theorem 2.1.** When $a_1 < -1$, the quadratic near-integrable system (3.1) can have small limit cycles bifurcating from the two centers (0, 0) and (1, 0) with distributions: (3, 0), (0, 3), (2, 0), (0, 2) and (1, 1). (2, 1)- or (1, 2)-distribution does not exist.

**Proof.** Consider system (3.1) for $a_1 < -1$. The system (3.1)$_{\varepsilon=0}$ is a reversible integrable system. In order to compute the Melnikov function near the two centers (0, 0) and (1, 0), we need transform system (3.1)$_{\varepsilon=0}$ to a Hamiltonian system. The integrating factor $\gamma$ is given in (3.1). Now, introducing $dt = \gamma d\tau$ into (3.1) yields the perturbed Hamiltonian system:

\[
\begin{aligned}
\frac{dx}{d\tau} &= \gamma(y + a_1 xy) + \varepsilon \gamma a_{10} x, \\
\frac{dy}{d\tau} &= \gamma(-x + x^2 + a_4 y^2) + \varepsilon \gamma (b_{01} y + b_{11} xy),
\end{aligned}
\]

with the Hamiltonian of (3.1)$_{\varepsilon=0}$, given by

\[
H(x, y) = \frac{1}{2} \text{sign}(1 + a_1 x) |1 + a_1 x|^{\frac{2a_4}{a_1}} \left[ y^2 + \frac{(1 + a_1 - a_4)(1 + 2a_4 x)}{a_4(a_1 - a_4)(a_1 - 2a_4)} - \frac{x^2}{a_1 - a_4} \right].
\]

for $a_4 \neq 0, a_1 \neq a_4, a_1 \neq 2a_4$. The cases $a_4 = 0, a_1 = a_4$ or $a_1 = 2a_4$ will not be considered in this paper.

Note that

\[
\begin{aligned}
h_{00} &= H(0, 0) = \frac{1 + a_1 - a_4}{2a_4(a_1 - a_4)(a_1 - 2a_4)}, & \text{for } 1 + a_1 x > 0, \\
h_{10} &= H(1, 0) = -\frac{(a_1 + 1)(a_4 + 1)}{2a_4(a_1 - a_4)(a_1 - 2a_4)}(-1 - a_1)^{\frac{2a_4}{a_1}}, & \text{for } 1 + a_1 x < 0.
\end{aligned}
\]

Since in this paper, we concentrate on the case that system (3.1)$_{\varepsilon=0}$ has only two centers, we assume $a_1 < -1, a_4 < 0$. Thus,

\[
\lim_{x \to -\frac{1}{a_1}} H(x, y) = +\infty \quad \text{and} \quad \lim_{x \to -\frac{1}{a_4}} H(x, y) = -\infty.
\]

It is easy to see from system (3.1) that the trajectories of (3.1)$_{\varepsilon=0}$ rotate around the center (0, 0) in the clock-wise direction, while rotate around the center (1, 0) in the counter clock-wise direction, as shown in Fig. 2. Thus, the values of $h$ in $H(x, y) = h$ are taken from the two intervals: $h \in (h_{00}, \infty)$ for $1 + a_1 x > 0$, and $h \in (-\infty, h_{10})$ for $1 + a_1 x < 0$. It should be noted that $h_{00}$ is not necessarily larger than $h_{10}$. The analyses on the two half-plane in the $x$-$y$ plane (see Fig. 2), divided by the singular line $1 + a_1 x = 0$, are independent.
Figure 2: A phase portrait of the reversible system (3.3) with two centers for $a_1 = -3$, $a_4 = -\frac{2}{3}$.

Next, introduce

$$L_h : H(x, y) = h \begin{cases} h \in (h_{00}, \infty), & \text{for } 1 + a_1 x > 0, \\ h \in (-\infty, h_{10}), & \text{for } 1 + a_1 x < 0, \end{cases}$$

and define the Melnikov function:

$$M(h, a_{ij}, b_{ij}) = \oint_{L_h} q(x, y, b_{ij}) dx - p(x, y, a_{ij}) dy, lb59$$

where $p(x, y, a_{ij}) = \gamma a_{10} x$ and $q(x, y, b_{ij}) = \gamma (b_{01} + b_{11} x) y$. Using the results in [19, 31, 32], we can expand $M$ near $h = h_{00}$ and $h = h_{10}$ as

$$M_0(h, a_{ij}, b_{ij}) = \mu_{00} (h - h_{00}) + \mu_{01} (h - h_{00})^2 + \mu_{02} (h - h_{00})^3$$

$$+ \mu_{03} (h - h_{00})^4 + O((h - h_{00})^5), \quad \text{for } 0 < h - h_{00} \ll 1,$$  

$$M_1(h, a_{ij}, b_{ij}) = \mu_{10} (h_{10} - h) + \mu_{11} (h_{10} - h)^2 + \mu_{12} (h_{10} - h)^3$$

$$+ \mu_{13} (h_{10} - h)^4 + O((h_{10} - h)^5), \quad \text{for } 0 < h_{10} - h \ll 1,$$  

where the coefficients $\mu_{ij}$, $i = 0, 1; j = 0, 1, 2, \cdots$ can be obtained by using the Maple programs developed in [33] as follows:

$$\mu_{00} = 2 \pi (a_{10} + b_{01}),$$

$$\mu_{01} = \cdots$$

$$\mu_{10} = \cdots$$

$$\mu_{11} = \cdots$$

$$\mu_{12} = \cdots$$

$$\mu_{13} = \cdots$$
\begin{align*}
\mu_{01} &= \frac{\pi}{12} \left[ (10 - 13 a_1 - 14 a_4 + 13 a_1^2 + 7 a_1 a_4 - 20 a_4^2) a_{10} \\
&\quad + (10 - a_1 + 10 a_4 + a_1^2 - 5 a_1 a_4 + 4 a_4^2) b_{01} + 12 (1 + a_4) b_{11} \right], \\
\mu_{02} &= \frac{\pi}{864} \left[ (1540 - 980a_1 - 280a_4 + 861a_1^2 - 1512a_1a_4 - 3984a_1^2 + 626a_4^2 + 1566a_1^3 + 1a_4^3 \\
&\quad + 1620a_1a_4^2 - 4432a_1^3 + 313a_4 - 1018a_1^2a_4 - 279a_1^2a_4^2 + 3080a_1a_4^3 - 2096a_4^3) a_{10} \\
&\quad + (1540 + 700a_1 + 3080a_4 + 21a_1^2 + 168a_1a_4 + 2772a_1^2 - 2a_1^3 + 126a_1a_4^2 \\
&\quad - 828a_1a_4^2 + 1424a_4^3 + a_4^4 - 58a_1^3a_4 + 369a_1^2a_4^2 - 712a_1a_4^3 + 400a_4^4) b_{01} \\
&\quad + 24 b_{11} (1 + a_4) (70 + 35a_1 + 70a_4 + a_1^2 - 17a_1a_4 + 52a_4^2) b_{11} \right], \\
\mu_{03} &= \frac{\pi}{622080} \left[ (3403400 - 300300a_1 + 3003000a_4 + 690690a_1^2 - 4984980a_1a_4 - 7327320a_4^2 \\
&\quad - 500885a_1^3 + 3314850a_1^2a_4 - 4430580a_1a_4^2 - 17811640a_4^3 + 323121a_1^4 \\
&\quad - 2444439a_1a_4 + 4201218a_1^2a_4^2 + 5794692a_1a_4^3 - 18033936a_4^4 - 168603a_1^5 \\
&\quad + 1420500a_1a_4^4 - 325351a_4^5 - 1296282a_1^2a_4^3 + 12107904a_4^6 \\
&\quad - 10462368a_4^5 + 56201a_1^6 - 520311a_1a_4^5 + 1471287a_1^2a_4^4 - 407053a_1^3a_4^3 \\
&\quad - 4589772a_1^2a_4^4 + 7149264a_1a_4^5 - 3159616a_4^6) a_{10} \\
&\quad + (3403400 + 3303300a_1 + 10212000a_4 + 690690a_1^2 + 5825820a_1a_4 \\
&\quad + 14294280a_1^2 + 11935a_4 + 404250a_1^3a_4 + 2721180a_1a_4^2 + 12236840a_4^3 \\
&\quad - 699a_1^4 - 11379a_1^3a_4 + 262458a_1^2a_4^2 - 1891308a_1a_4^3 + 694704a_4^4 \\
&\quad + 417a_1^5 + 1380a_1^4a_4 - 14909a_1^3a_4^2 + 1121838a_1^2a_4^3 - 2964576a_1a_4^4 \\
&\quad + 2670432a_1^4 - 139a_1^5 - 291a_1a_4^5 + 46227a_1^2a_4^4 - 366193a_1^3a_4^3 \\
&\quad + 1076988a_1^2a_4^4 - 1335216a_1a_4^5 + 578624a_4^6) b_{01} \\
&\quad + (3603600 + 3603600a_1 + 10810800a_4 + 790020a_1^2 + 6597360a_1a_4 \\
&\quad + 15024240a_1^2 + 12600a_1^3 + 480060a_1^4a_4 + 3764880a_1a_4^2 + 12514320a_4^3 \\
&\quad + 180a_1^4 - 108000a_1^3a_4 + 11340a_1^2a_4^2 - 618480a_1a_4^3 + 6566400a_4^4 \\
&\quad + 180a_1^4a_4 - 23400a_1^2a_4^2 + 321300a_1^3a_4^3 - 1389600a_1a_4^4 + 1869120a_1^5) b_{11} \right],
\end{align*}

and

\begin{align*}
\mu_{10} &= 2 \pi (-1 - a_1)^{3/2} \left[ (1 - 2 a_4) a_{10} + (1 + a_1) (b_{01} + b_{11}) \right], \\
\mu_{11} &= \frac{\pi}{12} (-1 - a_1)^{-2} \left( \frac{2(a_1 - a_0)}{a_1} \right) \\
&\times \left[ (10 + 33a_1 - 6a_4 + 36a_1^2 - 21a_1a_4 - 24a_1^2a_4 + 30a_1a_4^2 - 8a_4^3) a_{10} \\
&\quad + (1 + a_1) (10 + 21a_1 - 10a_4 + 12a_1^2 - 15a_1a_4 + 4a_4^2) b_{01} \\
&\quad - (1 + a_1) (1 + a_1) (2 + 3a_1 - 4a_4) b_{11} \right], \\
\mu_{12} &= \frac{\pi}{864} (-1 - a_1)^{-2} \left( \frac{3(a_1 - a_0)}{a_1} \right) \\
&\times \left[ (1540 + 7140a_1 - 2800a_4 + 13041a_1^2 - 11592a_1a_4 + 2212a_4^2 + 11448a_1^3 \right]
\end{align*}
or one center and one saddle point. For each point on the line segment $(0, a_4)$ and the distribution of the system's singularities. Therefore, for each point on the whole line and the coefficients $a_1, a_2, a_3, a_4$:

\[ a_1 = \frac{1}{3} (a_1 - 5) \]

\[ a_2 = \frac{1}{3} (6 a_1 + 5) (a_1 < -1) \]

Therefore, for each point on the line segment $a_4 = \frac{1}{3} (a_1 - 5)$ (see Fig. II), there always exist 3 small limit cycles bifurcating from the center $(0, 0)$, no matter whether the system has two centers, or one center and three saddle points, or one center and one saddle point. For each point on the line segment $a_4 = \frac{1}{3} (6 a_1 + 5) (a_1 < -1)$, the system can have 3 limit cycles bifurcating from the center $(1, 0)$. This indicates

\[
\begin{align*}
-18072a_1^2a_4 + 8628a_4a_1^2 - 1112a_3^2 + 752a_4^4 - 12024a_1a_4^2 + 12213a_1^2a_4^2 - 5232a_1a_4^3 \\
+ 4320a_1^3 - 1728a_1^4a_4 + 6192a_1^3a_4^2 - 7938a_1^2a_4^3 + 4272a_1^4a_4^4 - 800a_4^5 \end{align*}
\]

\[
+ (1 + a_1) (1540 + 5460a_1 - 3080a_4 + 7161a_4^2 - 9072a_3a_4 + 2772a_4^4 + 4014a_4^5 - 9030a_1a_4^2 - 6372a_1a_4^3 - 1424a_1a_4^4 + 864a_4^5 - 3096a_1^2a_4 + 3969a_1a_4^2 \\
- 2136a_1a_4^3 + 400a_4^4) b_{01} \\
- (1 + a_1)(1 + a_4) (140 + 420a_1 - 420a_4 + 423a_4^2 - 996a_1a_4 + 576a_4^2 \\
+ 144a_3^2 - 633a_1a_4 + 888a_1a_4^2 - 400a_4^3) b_{11}] \\
\mu_{13} = \frac{\pi}{1244160} (-1 - a_1)^{-\frac{2(a_1 - 3a_4)}{a_1}} \\
\times \left[(3403400 + 20720700a_1 - 9809800a_4 + 53243190a_1^2 - 54234180a_1a_4 + 13093080a_4^2 \\
+ 74334645a_1^3 - 123735150a_1^2a_4 + 65571660a_1a_4^2 - 10776920a_4^3 + 60023916a_4^4 \\
- 147900519a_1^3a_4 + 131934978a_1^2a_4^2 - 49682268a_1a_4^3 + 6439744a_4^4 + 27002160a_4^5 \\
+ 95460120a_1^3a_4 + 132380865a_1^2a_4^2 - 89408610a_1a_4^3 + 29027880a_4^4 - 3527040a_4^5 \\
+ 5443200a_1^6 - 28946160a_1^5a_4 + 63998532a_1^4a_4^2 - 74879613a_1^3a_4^3 + 48498336a_1^2a_4^4 \\
- 16296336a_1a_4^5 + 2181248a_4^6 - 1555200a_1^6a_4 + 9603360a_4^7a_4^2 - 24061752a_4^8a_4^3 \\
+ 31232358a_4^9a_4^4 - 22072536a_4^5a_4^5 + 8011296a_4^6a_4^6 - 1157248a_4^7a_4^7 \\
+ (1 + a_1) (3403400 + 17117100a_1 - 10210200a_4 + 35225190a_4^2 - 45225180a_1a_4 \\
+ 14294280a_1^3 + 37785825a_1^4 - 79202970a_1^2a_4 + 54455940a_1a_4^2 \\
- 12236840a_1^3 + 22125636a_1^4 - 68371209a_1^3a_4 + 77864598a_1^2a_4^2 \\
- 38601828a_1a_4^3 + 6629040a_1a_4^4 + 6629040a_1a_4^5 - 28984680a_1a_4^6 \\
+ 49687587a_1^3a_4^2 - 41614974a_1^2a_4^3 + 16953984a_1a_4^4 - 2670432a_4^5 \\
+ 777600a_4^6 - 4801680a_4^7a_4^2 + 12030876a_4^8a_4^3 - 15616179a_4^9a_4^4 \\
+ 11036268a_4^{10}a_4^5 - 4005648a_4^{11}a_4^6 + 578624a_4^{12}b_{01} \\
- (1 + a_1)(1 + a_4) (200200 + 900900a_1 - 800800a_4 + 1600830a_1^2 - 3132360a_1a_4 \\
+ 1530760a_1^3 + 1397655a_1^4 - 4596480a_1^2a_4 + 5008500a_1a_4^2 \\
- 1808240a_1^3 + 594864a_1^4 - 3001266a_1^2a_4 + 5594022a_1a_4^2 \\
- 4568112a_1^3a_4^2 + 1379936a_1^2a_4^3 + 97200a_1^4 - 736776a_1a_4^4 \\
+ 2162079a_1a_4^5 - 3080268a_1^2a_4^2 + 2136528a_1a_4^3 - 578624a_4^4) b_{11}] \\
\]
that the results given in [23, 24, 30] showing that the reversible near-integrable systems with one center and one saddle point can have maximal 2 limit cycles is conservative, since on the part of the line $a_4 = \frac{1}{3} (a_1 - 5)$ in the first quadrant ($a_1 > 5$) such a system can have at least 3 limit cycles.

First, we consider the maximal number of limit cycles which can bifurcate from the center $(0, 0)$. Setting $\mu_{00} = 0$ yields

$$b_{01} = -a_{10}, \quad lb62$$

and then we have

$$\mu_{01} = \pi \left[ (a_1 - 1 - a_4)(a_1 + 2a_4)a_{10} + (1 + a_4)b_{11} \right], \quad lb63$$

In order to have $\mu_{01} = 0$, we suppose $a_4 \neq -1$ and choose

$$b_{11} = -\frac{(a_1 - 1 - a_4)(a_1 + 2a_4)}{1 + a_4} a_{10}, \quad lb64$$

Then, $\mu_{02}$ and $\mu_{03}$ are simplified to

$$\mu_{02} = \frac{\pi}{3} a_1 (a_1 - a_4)(a_1 + 2a_4)(a_1 - 3a_4 - 5) a_{10},$$

$$\mu_{03} = -\frac{\pi}{144} a_1(a_1-a_4)(a_1+2a_4)(770 + 105a_1 + 1400a_4 + 42a_1^2 - 434a_4a_4$$

$$+ 1274a_4^2 - 13a_4^3 + 128a_4^2a_4 - 415a_1a_4^2 + 444a_4^3)a_{10}. \quad lb65$$

There are five choices for $\mu_{02} = 0$. Except the choice $a_1 - 3a_4 - 5 = 0$, all other choices lead to $\mu_{0i} = 0$, $i = 3, 4, \cdots$. Thus, letting

$$a_4 = \frac{1}{3} (a_1 - 5), \quad lb66$$

which implies $a_1 \neq 2$ when $a_4 \neq -1$. Since we assume $a_1 < -1$, for this case (i.e., when the condition (??) holds), $a_4 \neq -1$ is guaranteed. Then, we have

$$\mu_{03} = -\frac{25\pi}{162} a_1(a_1 + 1)(a_1 - 2)^2(2a_1 + 5)a_{10},$$

$$\mu_{04} = -\frac{5\pi}{8748} a_1(a_1 + 1)(a_1 - 2)^2(2a_1 + 5)(a_1 + 4)(17a_1 + 518)a_{10}$$

$$\vdots$$

$$\mu_{10} = -\frac{10\pi}{3} (-1 - a_1)^{-3/2} a_1(2a_1 + 5)a_{10},$$

$$\mu_{11} = \frac{25\pi}{324} (-1 - a_1)^{-3(2a_1 + 5)} a_1(a_1 - 2)^2(2a_1 + 5)a_{10},$$

$$\vdots$$

implying that in addition we need
(2a_1 + 5)a_{10} \neq 0. lb67

Under the above conditions (?), (?), (?), and (?), we obtain \( \mu_{00} = \mu_{01} = \mu_{02} = 0, \) but \( \mu_{03} \neq 0, \) \( \mu_{10} \neq 0. \) Hence, at most 3 small limit cycles can bifurcate from the center \((0,0)\) with no limit cycles bifurcating from the center \((1,0)\). Further, giving proper perturbations to the parameters \(a_4\) (or \(a_1\)), \(b_{11}\) and \(b_{01}\), we can obtain 3 small limit cycles bifurcating from the origin. This shows that the conclusion is true for the case of \((3,0)\)-distribution.

Next, consider the \((0,3)\)-distribution. Similarly, letting \(\mu_{10} = 0\) yields

\[
b_{01} = -b_{11} + \frac{2a_4 - 1}{1 + a_1} a_{10} lb68
\]

(3.13)

Then, \(\mu_{11}\) becomes

\[
\mu_{11} = \pi(-1-a_1) \frac{2(\alpha_1-a_4)}{\alpha_1} \left[(a_1+2a_4)(2a_1-a_4+1)a_{10}-(1+a_1)^2(a_1-a_4+1)b_{11}\right] lb69
\]

Hence, we set

\[
b_{11} = \frac{(a_1+2a_4)(2a_1-a_4+1)}{(1+a_1)^2(a_1-a_4+1)} a_{10}, \quad (a_1-a_4+1 \neq 0), lb70
\]

(3.15)

to yield \(\mu_{11} = 0, \) and

\[
\mu_{12} = \frac{\pi}{3}(-1-a_1) \frac{5a_1-a_4}{2a_1} a_1 (a_1-a_4) (a_1+2a_4)(6a_1-3a_4+5)a_{10},
\]

\[
\mu_{13} = \frac{\pi}{288} (-1-a_1) \frac{2(\alpha_1-3a_4)}{\alpha_1} a_1 (a_1-a_4) (a_1+2a_4) (770+2205a_1-1400a_4+2142a_1^2 lb71
\]

\[
-3234a_1a_4+1274a_1^2-720a_4^2-1962a_1^2a_4+1689a_1a_4^2-444a_1^3) a_{10}.
\]

(3.16)

The only choice for \(\mu_{12} = 0\) is \(6a_1 - 3a_4 + 5 = 0, \) from which we have

\[
a_4 = \frac{1}{3} (6a_1 + 5) lb72
\]

(3.17)

This implies that \(a_1 - a_4 + 1 = -(a_1 + \frac{2}{3}) > 0\) for \(a_1 < -1.\) Further, we obtain

\[
\mu_{13} = \frac{-25\pi}{324} (-1-a_1) \frac{10+11a_1}{\alpha_1} a_1 (3a_1+2)(3a_1+5)a_{10},
\]

\[
\mu_{14} = \frac{-5\pi}{17496} (-1-a_1) \frac{30+87a_1}{\alpha_1} a_1 (3a_1+2)(3a_1+5)(3a_1+4)(501a_1+518)a_{10}
\]

\[\vdots\]

\[
\mu_{00} = \frac{10\pi}{3(1+a_1)^2} a_1 (3a_1+5)a_{10},
\]

\[
\mu_{01} = \frac{-25\pi}{324(1+a_1)^2} a_1 (3a_1+5)(3a_1+2)^2a_{10},
\]

\[\vdots\]
implying that in addition we require
\[(3a_1 + 5)a_{10} \neq 0.\]

Under the above conditions (??), (??), (??) and (??), we have \(\mu_{10} = \mu_{11} = \mu_{12} = 0\), but \(\mu_{13} \neq 0\), \(\mu_{00} \neq 0\). Further, by properly perturbing the parameters \(a_4\) (or \(a_1\)), \(b_{11}\) and \(b_{01}\), we can obtain 3 small limit cycles bifurcating from the center \((1,0)\), but no limit cycles from the origin. This proves the case of \((0,3)\)-distribution.

For the case of \((2,0)\)-distribution, it follows from the conditions (??) and (??), and \(a_4 \neq -1\) that \(\mu_{00} = \mu_{01} = 0\), and
\[
\mu_{02} = \frac{\pi}{3} a_1 (a_1 - a_4) (a_1 + 2a_4)(a_1 - 3a_4 - 5) a_{10},
\]
\[
\mu_{10} = -\frac{2\pi}{(1 + a_4)(-1 - a_1)^{3/2}} a_1 (a_1 - a_4)(a_1 + 2a_4) a_{10}.
\]
Thus, \(\mu_{02} \neq 0\) implies \(\mu_{10} \neq 0\), indicating that the conclusion holds for the case of \((2,0)\)-distribution. if \(a_4 = -1\).

When \(a_4 = -1\), (??) becomes
\[
\mu_{01} = \pi a_1 (a_1 - 2)a_{10} \neq 0 \quad \text{for} \quad a_1 < -1 \quad \text{and} \quad a_{10} \neq 0.
\]
Under the conditions \(b_{01} = -a_{10}\) and \(a_4 = -1\), \(\mu_{10}\) and \(\mu_{11}\) becomes
\[
\mu_{10} = -2\pi(-1 - a_1)^{-3/2} [(a_1 - 2)a_{10} - (1 + a_1)b_{11}],
\]
\[
\mu_{11} = \pi(-1 - a_1)^{-\frac{2(a_1 + 2)}{a_1}} a_1 (a_1 - 2)a_{10},
\]
which shows that \(\mu_{11} \neq 0\) for \(a_1 < -1\) and \(a_{10} \neq 0\). But we can choose
\[
b_{11} = \frac{a_1 - 2}{1 + a_1} a_{10}
\]
to obtain \(\mu_{10} = 0\). Thus, for this case we have a \((1,1)\)-distribution.

Similarly, for the \((0,2)\)-distribution, we use the conditions (??) and (??) to obtain
\[
\mu_{12} = \frac{\pi}{3} (-1 - a_1)^{-5/2 - 6a_4} a_1 (a_1 - a_4)(a_1 + 2a_4)(6a_1 - 3a_4 + 5)a_{10},
\]
\[
\mu_{00} = \frac{2\pi}{(1 + a_4)^2(a_1 - a_4 + 1)} a_1 (a_1 - a_4)(a_1 + 2a_4)a_{10}.
\]
This indicates that \(\mu_{12} \neq 0\) implies \(\mu_{00} \neq 0\), and so the conclusion for the case of \((0,2)\)-distribution is also true if \(a_1 - a_4 + 1 \neq 0\).

When \(a_1 - a_4 + 1 = 0\), i.e., \(a_4 = a_1 + 1 < 0\), (??) is reduced to
\[
\mu_{11} = \pi(-1 - a_1)^{-\frac{2(a_1 + a_4)}{a_1}} a_1(3a_1 + 2)a_{10} \neq 0 \quad \text{for} \quad a_1 < -1 \quad \text{and} \quad a_{10} \neq 0,
\]
and \( \mu_{00} \) and \( \mu_{01} \) become

\[
\mu_{00} = \frac{2\pi}{1 + a_1} \left[ (a_1 + 2) a_{10} - (1 + a_1) b_{11} \right], \\
\mu_{01} = -\frac{\pi}{1 + a_1} a_1 (3 a_1 + 2) a_{10},
\]

which clearly shows that \( \mu_{01} \neq 0 \) for \( a_1 < -1 \) and \( a_{10} \neq 0 \). However, we may choose

\[
b_{11} = \frac{a_1 + 2}{1 + a_1} a_{10}
\]

to obtain \( \mu_{00} = 0 \). Thus, for \( a_1 - a_4 + 1 = 0 \), we have a \((1, 1)\)-distribution.

Finally, suppose the condition given in (??) is satisfied, i.e., \( b_{01} = -a_{10} \), then substituting this into \( \mu_{10} \) to solve \( b_{11} \) to obtain

\[
b_{11} = \frac{a_1 + 2 a_4}{1 + a_1} a_{10}
\]

Then, under the conditions (??) and (??), we obtain

\[
\mu_{01} = \frac{\pi}{1 + a_1} a_1 (a_1 - a_4) (a_1 + 2 a_4) a_{10}, \\
\mu_{11} = -\pi (-1 - a_1)^{-2} a_1 (a_1 - a_4) (a_1 + 2 a_4) a_{10},
\]

which shows that \( \mu_{01} \neq 0 \) implies \( \mu_{11} \neq 0 \), and thus in general the conclusion is true for the case of \((1, 1)\)-distribution.

As we have seen in the above analysis, if the condition (??), \( a_4 = \frac{1}{3} (a_1 - 5) \), is not used, then we can only have 2 limit cycles bifurcating from the center \((1, 0)\). In other words, we can obtain one more limit cycle, by using the condition \( a_4 = \frac{1}{3} (a_1 - 5) \), only bifurcating from the center \((0, 0)\). Similarly, if the condition (??), \( a_4 = \frac{1}{3} (6 a_1 + 5) \), is not used, then we can have only 2 limit cycles bifurcating from the center \((1, 0)\), but no limit cycles can bifurcate from the origin. Then, condition \( a_4 = \frac{1}{3} (6 a_1 + 5) \) can be only used to get one more limit cycle around the center \((1, 0)\), rather than the origin. Therefore, \((2, 1)\)- or \((1, 2)\)-distribution is not possible.

This completes the proof of Theorem 2.1. \( \square \)

4 Limit cycles bifurcating from closed orbits

In this section, based on the results of the small limit cycles obtained in the previous section, we want to investigate the possibility of existence of large limit cycles by applying the Melnikov function, defined in (??). We have the following result.

**Theorem 4.1.** For the case of bifurcation of small limit cycles from the two centers \((0, 0)\) and \((1, 0)\) with \((3, 0)\)-distribution (respectively, \((0, 3)\)-distribution) there exists at least one
large limit cycle near \( L_h \) for some \( h \in (-\infty, h_{10}) \) (respectively for some \( h \in (h_{00}, \infty) \)). For the case of limit cycles with \((2,0)\)-distribution (respectively, \((0,2)\)-distribution) there exist at least two large limit cycles, one near \( L_{h_1} \), for some \( h_1 \in (-\infty, h_{10}) \) and one near \( L_{h_2} \) for some \( h_2 \in (h_{00}, \infty) \). The corresponding values of the parameters \( a_1 \) and \( a_4 \) for the existence of 4 limit cycles can appear at least in some regions in the \( a_1-a_4 \) parameter plane.

**Remark 4.2.** Theorem 4.1 gives a positive answer to the open question of existence of limit cycles in near-integrable quadratic systems: at least 4 limit cycles can exist. For the case of \((1,1)\)-distribution, so far no more large limit cycles have been found.

**Proof.** It follows from (??) with

\[
p(x, y, a_{ij}) = |1 + a_1 x|^{-\frac{a_1 + 2a_4}{a_1}} a_{10} x, \quad q(x, y, b_{ij}) = |1 + a_1 x|^{-\frac{a_1 + 2a_4}{a_1}} (b_{01} + b_{11} x) y
\]

that

\[
M(h, a_1, a_4, a_{10}, b_{01}, b_{11}) = \oint_{L_h} q(x, y, b_{ij}) \, dx - p(x, y, a_{ij}) \, dy
\]

\[
= \oint_{L_h} q(x, y, b_{ij}) \, dx - \oint_{L_h} p(x, y, a_{ij}) \, dy
\]

\[
= \oint_{L_h} q(x, y, b_{ij}) \, dx + \oint_{L_h} y p_x(x, y, a_{ij}) \, dx
\]

\[
= \oint_{L_h} \left[ q(x, y, b_{ij}) + y p_x(x, y, a_{ij}) \right] \, dx
\]

\[
= \oint_{L_h} \left[ |1 + a_1 x|^{-\frac{a_1 + 2a_4}{a_1}} (b_{01} + b_{11} x) \right] \, y \, dx
\]

\[
= \oint_{L_h} \left[ |1 + a_1 x|^{-\frac{a_1 + 2a_4}{a_1}} \left( a_{10} (1 + a_1 x) \right) \right] \, y \, dx
\]

\[
= (a_{10} + b_{01}) I_0(h, a_1, a_4) + b_{11} I_1(h, a_1, a_4) + a_{10} I_2(h, a_1, a_4)
\]

\[
\equiv \begin{cases} 
M_0(h, a_1, a_4, a_{10}, b_{01}, b_{11}) \text{ for } h \in (h_{00}, \infty), & \text{when } 1 + a_1 x > 0, \\
M_1(h, a_1, a_4, a_{10}, b_{01}, b_{11}) \text{ for } h \in (-\infty, h_{10}), & \text{when } 1 + a_1 x < 0,
\end{cases}
\]

where

\[
I_0(h, a_1, a_4) = \oint_{L_h} |1 + a_1 x|^{-\frac{a_1 + 2a_4}{a_1}} y \, dx
\]

\[
= \begin{cases} 
2 \int_{x_{\min}}^{x_{\max}} (1 + a_1 x)^{-\frac{a_1 + 2a_4}{a_1}} y_+ \, dx, & \forall \ h \in (h_{00}, \infty), & \text{when } 1 + a_1 x > 0, \\
-2 \int_{x_{\min}}^{x_{\max}} (-1 - a_1 x)^{-\frac{a_1 + 2a_4}{a_1}} y_+ \, dx, & \forall \ h \in (-\infty, h_{10}), & \text{when } 1 + a_1 x < 0;
\end{cases}
\]

\[
I_1(h, a_1, a_4) = \oint_{L_h} |1 + a_1 x|^{-\frac{a_1 + 2a_4}{a_1}} x \, y \, dx
\]
\[ H(x, y) = \frac{16807 (16250 y^2 + 13650 x^2 + 2730 x - 441)}{32500 (7 - 30 x)(40353607 - 172944030 x)^{4/9}} \quad \text{for} \quad x \neq \frac{7}{30}, \]

with \( h_{00} = -\frac{441}{32500} \) and \( h_{10} = -\frac{33957 (\frac{23}{7})^{5/9}}{747500}. \)

The Melnikov functions \( M_i(h, a_{10}) \) can be expressed as

\[ M_i(h, a_{10}) = M_{i0}(h) a_{10}, \quad i = 0, 1, \ldots, 80 \]
Figure 3: Functions $M_{00}(h)$ and $M_{10}(h)$ under the conditions $\mu_{00} = \mu_{01} = \mu_{02} = 0$, $\mu_{03} \neq 0$ and $\mu_{10} \neq 0$, for $a_1 = -\frac{30}{7}$ and $a_4 = \frac{1}{3}(a_4 - 5) = -\frac{65}{21}$. (a) $M_{00}(h) > 0$ for $h \in [h_{00}, +\infty)$, with $h_0 = -\frac{441}{32500} \approx -0.01357$; and (b) $M_{10}(h)$ for $h \in (-\infty, h_{10}]$, with $h_{10} = -\frac{33957}{4775900} \approx -0.08797$, crossing the $h$-axis at $h = h_1^* \in (-0.9250363254, -0.9250363253)$. 
Figure 4: Illustration of the existence of 4 limit cycles when $a_1 = -\frac{30}{7}, \quad a_4 = \frac{1}{7}(a_1 - 5) = -\frac{65}{21} - \varepsilon_1$, and $a_{10} = \frac{1}{2000}, \quad b_{11} = \frac{230}{21} a_{10} - \varepsilon_2, \quad b_{01} = -a_{10} - \varepsilon_3$, where $0 \leq \varepsilon_3 \ll \varepsilon_2 \ll \varepsilon_1 \ll \varepsilon$: (a) An unstable large limit cycle enclosing the center $(1, 0)$; and (b) Zoomed area around the center $(0, 0)$ showing the existence of 3 small limit cycles.
Without loss of generality, we may assume

$$a_{10} > 0, lb81$$

and thus $M_i(h, a_{10})$ and $M_{10}(h)$ have the same sign. It is noted that for the above chosen parameter values, we have

$$\mu_{03} = \frac{139150000 \pi}{453789} a_{10} > 0 \quad \text{and} \quad \mu_{10} = -\frac{2500\sqrt{161} \pi}{3703} a_{10} < 0.$$

The computation results of $M_{00}(h)$ for $h \in (h_{00}, \infty)$ and $M_{10}(h)$ for $h \in (\infty, h_{10})$ are shown, respectively, in Figs. 3(a) and 3(b). Figure 3(a) shows that $M_{00}(h) > 0$ for $h \in (h_{00}, \infty)$, and its sign agrees with that of $\mu_{03} > 0$ for $0 < h - h_{00} \ll 1$, as expected. It is also noted, as shown in Fig. 3(b), that the sign of $M_{10}(h)$ agrees with that of $\mu_{10} < 0$ for $0 < h_{10} - h \ll 1$. However, unlike the interval $h \in (h_{00}, \infty)$, this interval contains a critical value $h = h_1^* \in (-0.9250363254, -0.9250363253)$ at which $M_{10}(h_1^*) = 0$ and the function $M_{10}(h)$ changes its sign as $h$ crosses this critical point. Thus, for this case, besides the 3 small limit cycles, there exists at least one large limit cycle bifurcating from the closed orbit $L_{h_1^*}$ of (??). This large limit cycle is shown in Fig. 4(a), which encloses the center $(1, 0)$; and Fig. 4(b) illustrates the existence of 3 small limit cycles around the center $(0, 0)$.

(B) For the case of the $(0, 3)$-distribution, we have

$$a_4 = \frac{1}{3}(6a_1 + 5), \quad b_{01} = -b_{11} + \frac{2a_4 - 1}{1 + a_1} a_{10}, \quad b_{11} = \frac{(a_1 + 2a_4)(2a_1 - a_4 + 1)}{(1 + a_1)^2(a_1 - a_4 + 1)} a_{10}.$$

By choosing $a_1 = -\frac{70}{51}$, we have $a_4 = -\frac{55}{51}, b_{01} = -\frac{5611}{361} a_{10}$ and $b_{11} = \frac{8670}{361} a_{10}$. The point $(a_1, a_4) = (\frac{70}{51}, \frac{55}{51})$ is marked by a blank circle on the line $a_4 = \frac{1}{3}(6a_1 + 5)$ in the $a_1$-$a_4$ parameter plane (see Fig. 1). Moreover,

$$\gamma = \left(1 - \frac{70}{51} x\right)^{-\frac{48}{37}} \quad (x \neq \frac{51}{70}),$$

and the Hamiltonian is

$$H(x, y) = \frac{345025251 (2750 y^2 + 9350 x^2 - 16830 x + 7803)}{5500 (51 - 70 x)(897410677851 - 1231740146070 x)^{4/7}} \quad \text{for} \quad x \neq \frac{51}{70},$$

with

$$h_{00} = \frac{7803}{5500} > h_{10} = -\frac{44217}{104500} \left(\frac{19}{51}\right)^{3/7}.$$

For this case, $\mu_{00}$ and $\mu_{13}$ become

$$\mu_{00} = -\frac{10500 \pi}{361} a_{10} < 0 \quad \text{and} \quad \mu_{13} = \frac{4561235000}{565036352721} \left(\frac{51}{19}\right)^{2/7} a_{10} > 0.$$

The computation results of $M_{00}(h)$ for $h \in (h_{00}, \infty)$ and $M_{10}(h)$ for $h \in (\infty, h_{10})$ are shown in Figs. 5(a) and 5(b), respectively. As shown in Fig. 5(a), the sign of $M_{00}(h)$ agrees with that of $\mu_{00} < 0$ for $0 < h - h_{00} \ll 1$, and in addition the function $M_{00}(h)$
Figure 5: Functions $M_{00}(h)$ and $M_{10}(h)$ under the conditions $\mu_{10} = \mu_{11} = \mu_{12} = 0$, $\mu_{13} \neq 0$ and $\mu_{00} \neq 0$, for $a_1 = -\frac{70}{51}$ and $a_4 = \frac{1}{3}(6a_1 + 5) = -\frac{55}{51}$. (a) $M_{00}(h)$ for $h \in [h_0, +\infty)$, with $h_0 = \frac{7803}{5500} \approx 1.41873$, crossing the $h$-axis at $h = h_2^* \in (13.3847179116, 13.3847179117)$; and (b) $M_{10}(h) > 0$ for $h \in (-\infty, h_1]$, with $h_1 = -\frac{44217}{103990} \approx -0.27714$. 

(a) $M_{00}$

(b) $M_{10}$
Figure 6: Illustration of the existence of 4 limit cycles when $a_1 = -\frac{70}{51}$, $a_4 = \frac{1}{3}(6a_1 + 5) = -\frac{55}{51} - \varepsilon_1$, and $a_{10} = 10$, $b_{11} = \frac{8670}{361} a_{10} - \varepsilon_2$, $b_{01} = -\frac{5611}{361} a_{10} + \varepsilon_3$, where $0 < \varepsilon_3 \ll \varepsilon_2 \ll \varepsilon_1 \ll \varepsilon$: (a) An unstable large limit cycle enclosing the center $(0, 0)$; and (b) Zoomed area around the center $(1, 0)$ showing the existence of 3 small limit cycles.
crosses a critical value at $h = h_2^* \in (13.3847179116, 13.3847179117)$, at which it changes sign. Figure 5(b) shows that $M_{10}(h) > 0$ for $h \in (-\infty, h_{10})$, and its sign agrees with that of $\mu_{13} > 0$ for $0 < h_{10} - h \ll 1$. Hence, for this case, in addition to the 3 small limit cycles, there also exists at least one large limit cycle bifurcating from the closed orbit $L_{h_2^*}$ of (??). This large limit cycle is depicted in Fig. 6(a), which encloses the center $(0,0)$; and Fig. 6(b) illustrates the existence of 3 small limit cycles around the center $(1,0)$.

(C) Now consider the $(2,0)$-distribution. For this case, the condition $a_4 = \frac{1}{3}(a_1 - 5)$ is not used. We need to determine the values for both $a_1$ and $a_4$. We choose

$$a_1 = -4, \quad a_4 = -\frac{18}{5},$$

which represents a point in the third quadrant of the $a_1$-$a_4$ parameter plane (see the dark circle in Fig. 1 near the line $a_4 = \frac{1}{3}(a_1 - 5)$). Thus,

$$\gamma = \left(1 - 4x\right)^{\frac{1}{14}} (x \neq \frac{1}{4}).$$

In addition, we have $b_{01} = -a_{10}$, $b_{11} = \frac{392}{65} a_{10}$, and

$$H(x,y) = \frac{192 y^2 + 480 x^2 - 180 x + 25}{384 (1 - 4x)^{9/5}} \quad \text{for} \quad x \neq \frac{1}{4},$$

with

$$h_{00} = \frac{25}{384} > h_{10} = -\frac{325}{3456} \quad 3^{1/5}.$$

For this case, $\mu_{02}$ and $\mu_{10}$ are reduced to

$$\mu_{02} = -\frac{1344}{125} \pi a_{10} < 0 \quad \text{and} \quad \mu_{10} = -\frac{40 \sqrt{3}}{9} \pi a_{10} < 0.$$

The computation results of $M_{00}(h)$ for $h \in (h_{00}, \infty)$ and $M_{10}(h)$ for $h \in (-\infty, h_{10})$ are shown, respectively, in Figs. 7(a) and 7(b). As shown in Fig. 7(a), the sign of $M_{00}(h)$ agrees with that of $\mu_{02} < 0$ for $0 < h - h_{00} \ll 1$. Moreover, the function $M_{00}(h)$ crosses a critical value at $h = h_3^* \in (0.1448192224, 0.1448192225)$ at which it changes sign. Figure 7(b) shows $M_{10}(h)$ for $h \in (-\infty, h_{10})$, whose sign agrees with that of $\mu_{10} < 0$ for $0 < h_{10} - h \ll 1$. Also, $M_{10}(h)$ crosses a critical value at $h = h_4^* \in (-0.5822537644, -0.5822537643)$ at which it changes sign. Therefore, for this case, besides the two small limit cycles, there exist at least two large limit cycles bifurcating from the two different closed orbits $L_{h_3^*}$ and $L_{h_4^*}$ of (??). One large limit cycle surrounding the center $(1,0)$ is shown in Fig. 8(a), while another large limit cycle enclosing the center $(0,0)$ with 2 small limit cycles is depicted in Fig. 8(b).

(D) Finally, consider the $(0,2)$-distribution. For this case, the condition $a_4 = \frac{1}{3}(6 a_1 + 5)$ is not used. Taking

$$a_1 = -\frac{4}{3}, \quad a_4 = -\frac{6}{5},$$
Figure 7: Functions $M_{00}(h)$ and $M_{10}(h)$ under the conditions $\mu_{00} = \mu_{01} =, \mu_{02} \neq 0$ and $\mu_{10} \neq 0$, for $a_1 = -4$ and $a_4 = -\frac{18}{5}$. (a) $M_{00}(h)$ for $h \in [h_0, +\infty)$, with $h_0 = \frac{25}{384} \approx 0.06510$, crossing the $h$-axis at $h = h_3^* \in (0.1448192224, 0.1448192225)$; and (b) $M_{10}(h)$ for $h \in (-\infty, h_1]$, with $h_{10} = -\frac{325}{3456}3^{1/5} \approx -0.11715$, crossing the $h$-axis at $h = h_4^* \in (-0.5822537644, -0.5822537644)$. 
Figure 8: Illustration of the existence of 4 limit cycles when $a_1 = -4$, $a_4 = -\frac{18}{5}$, and $a_{10} = \frac{1}{100}$, $b_{11} = \frac{392}{65} a_{10} - \varepsilon_1$, and $b_{01} = -a_{10} - \varepsilon_2$, where $0 < \varepsilon_2 \ll \varepsilon_1 \ll \varepsilon$: (a) An unstable large limit cycle enclosing the center $(1,0)$; and (b) Zoomed area around the center $(0,0)$ showing the existence of 1 large limit cycle and 2 small limit cycles.
Figure 9: Functions $M_{00}(h)$ and $M_{10}(h)$ under the conditions $\mu_{10} = \mu_{11} = \mu_{12} \neq 0$ and $\mu_{00} \neq 0$, for $a_1 = -\frac{4}{3}$ and $a_4 = -\frac{6}{5}$. (a) $M_{00}(h)$ for $h \in [h_{00}, +\infty)$, with $h_0 = \frac{325}{128} \approx 2.53096$, crossing the $h$-axis at $h = h_{00}^* \in (12.6197809949, 12.6197809950)$; and (b) $M_{10}(h)$ for $h \in (-\infty, h_1]$, with $h_{10} = -\frac{75}{128} \approx -1.41107$, crossing the $h$-axis at $h = h_{10}^* \in (-3.1388150376, -3.1388150375)$. 
Figure 10: Illustration of the existence of 4 limit cycles when $a_1 = -\frac{4}{3}$, $a_4 = -\frac{6}{5}$, and $a_{10} = 1$, $b_{11} = \frac{1176}{65} a_{10} - \varepsilon_1$, $b_{01} = -\frac{513}{65} a_{10} + \varepsilon_2$, where $0 < \varepsilon_2 \ll \varepsilon_1 \ll \varepsilon$: (a) An unstable large limit cycle enclosing the center $(0,0)$; and (b) Zoomed area around the center $(1,0)$ showing the existence of 1 large limit cycle and 2 small limit cycles.
yields
\[
\gamma = \left(1 - \frac{4}{3}x\right)^{-\frac{4}{5}} (x \neq \frac{3}{4}).
\]
The point \((-\frac{4}{3}, -\frac{6}{5})\) is marked by a dark circle near the line \(a_4 = \frac{1}{3}(6a_1 + 5)\) in the \(a_1-a_4\) parameter plane (see Fig. 1). Further, we have \(b_{01} = -\frac{513}{65}a_{10}, \quad b_{11} = \frac{1176}{65}a_{10}, \quad \text{and} \quad H(x, y) = \frac{243(64y^2 + 480x^2 - 780x + 325)((3 - 4x)(324x - 243)^{4/5}}{((3 - 4x)(324x - 243)^{4/5}} \quad \text{for} \quad x \neq \frac{3}{4},
\]
with
\[
h_{00} = \frac{325}{128} > h_{10} = -\frac{75}{128} 3^{4/5}.
\]
For this case, \(\mu_{00}\) and \(\mu_{12}\) are simplified as
\[
\mu_{00} = -\frac{896}{65} \pi a_{10} < 0 \quad \text{and} \quad \mu_{12} = -\frac{448}{30375} 3^{9/10} \pi a_{10} < 0.
\]

The computation results of \(M_{00}(h)\) for \(h \in (h_{00}, \infty)\) and \(M_{10}(h)\) for \(h \in (-\infty, h_{10})\) are shown in Figs. 9(a) and 9(b), respectively. As shown in Fig. 9(a), the sign of \(M_{00}(h)\) agrees with that of \(\mu_{00} < 0\) for \(0 < h - h_{00} \ll 1\), and the function \(M_{00}(h)\) crosses a critical value at \(h = h^*_5 \in (12.6197809949, 12.6197809950)\) at which it changes sign. Figure 9(b) shows \(M_{10}(h)\) for \(h \in (-\infty, h_{10})\), whose sign agrees with that of \(\mu_{12} < 0\) for \(0 < h_{10} - h \ll 1\). Moreover, \(M_{10}(h)\) crosses a critical value at \(h = h^*_6 \in (-3.1388150376, -3.1388150375)\) at which it changes sign. Therefore, for this case, in addition to the two small limit cycles, there also exist at least two large limit cycles bifurcating from the two different closed orbits \(L_{h^*_5}\) and \(L_{h^*_6}\) of (4.3). One large limit cycle surrounding the center \((0, 0)\) is shown in Fig. 10(a), while another large limit cycle enclosing the center \((1, 0)\) with 2 small limit cycles is depicted in Fig. 10(b).

It is noted that all the four sets of values of \(a_1\) and \(a_4\) chosen above in (A), (B), (C) and (D) satisfy
\[
a_1 + 2a_4 \quad \text{for} \quad 0 < x \ll 1, \quad \text{where} \quad n \quad \text{is an integer and} \quad m \quad \text{is an odd integer,} \quad lb82 \quad (4.5)
\]
so that a consistent integrating factor (and so a consistent Hamiltonian function for the whole transformed system) is obtained. However, this condition is not necessary since the singular line \(1 + a_1 x = 0\) divides the phase plane into two parts, and the analysis does not need the continuity on the singular line. To demonstrate this, in the following we present a case for which the condition (4.5) is not satisfied. Consider the \((2, 0)\)-distribution, and choose \(a_1 = -5\) and \(a_4 = -4\). The point \((a_1, a_4) = (-5, -4)\) is marked by a dark circle in the \(a_1-a_4\) parameter plane (see Fig. 11). Then,
\[
a_1 + 2a_4 \quad \text{for} \quad 0 < x \ll 1, \quad b_{01} = a_{10}, \quad b_{11} = \frac{26}{3} a_{10},
\]
and
\[ H(x, y) = \begin{cases} \frac{x^2 + y^2}{2(1 - 5x)^{8/5}}, & \forall h \in (0, \infty), \quad \text{when } x < \frac{1}{5}, \\ -\frac{x^2 + y^2}{2(1 - 5x)^{8/5}}, & \forall h \in (-\infty, -\frac{1}{32}2^{4/5}), \quad \text{when } x > \frac{1}{5}. \end{cases} \]

For this case, \( \mu_{02} \) and \( \mu_{10} \) become

\[ \mu_{02} = -\frac{130}{3} \pi a_{10} < 0 \quad \text{and} \quad \mu_{10} = -\frac{65}{12} \pi a_{10} < 0. \]

The computation result of \( M_{00}(h) \) shows that \( M_{00}(h) < 0 \) for \( 0 < h \ll 1 \), agrees with the sign of \( \mu_{02} \). Moreover, \( M_{00}(0.1) = 0.0510077880 > 0 \), implying that there exists \( h = h_7^* \in (0, 0.1) \) such that \( M_{00}(h_7^*) = 0 \), and so a large limit cycle bifurcates from the closed orbit \( L_{h_7^*} \) of \( (??) \). The result of \( M_{10}(h) \) also shows that \( M_{10}(h) < 0 \) for \( 0 < -\frac{1}{32}2^{4/5} - h \ll 1 \), agreeing with the sign of \( \mu_{10} \), and that \( M_{10}(-\frac{1}{32}2^{4/5} - 0.8) = 7.4630743072 > 0 \), implying the existence \( h = h_8^* \in (-\frac{1}{32}2^{4/5} - 0.8, -\frac{1}{32}2^{4/5}) = (-0.8544094102, -0.0544094102) \) such that \( M_{10}(h_8^*) = 0 \). Thus, there exists another large limit cycle bifurcating from the closed orbit \( L_{h_8^*} \) of \( (??) \). Therefore, this case exhibits 2 small limit cycles and 2 large limit cycles, leading to the existence of at least 4 limit cycles.

Summarizing the above results with the continuity of parameters \( a_1 \) and \( a_4 \) shows that at least for some regions in the \( a_1-a_4 \) parameter plane the reversible near-integrable system \( (??) \) can exhibit at least 4 limit cycles around the two singular points \((0, 0)\) and \((1, 0)\) with distribution ether \((3, 1)\) or \((1, 3)\).

The proof of Theorem 4.1 is finished. \( \square \)

### 5 Conclusion

In this paper, we have proved that a quadratic non-Hamiltonian integrable system with two centers can have at least 4 limit cycles under quadratic perturbations, with distributions either \((3, 1)\) or \((1, 3)\). This result gives a new record, answering the open problem of the existence of limit cycles in near-integrable quadratic systems. It is shown that such systems can have at least 4 limit cycles for some regions in the 2-dimensional parameter plane, associated with the parameters of the integrable systems. Further research is needed on global analysis for all possible parameter values in the parameter plane.

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References

[1] D. Hilbert, Mathematical problems. (M. Newton, Transl.) Bull. Amer. Math. 8, 437–479, 1902.

[2] S. Smale, Mathematical problems for the next century. The Math. Intell. 20, 7–15, 1998.

[3] Yu. S. Ilyashenko and S. Yakovenko, Finitely smooth normal forms of local families of
diffeomorphisms and vector fields. Russ. Math. Surv. 46, 3–19, 1991.

[4] J. Écalle, Introduction aux fonctions analysables et preuve constructive de la conjecture
de Dulac (French). Hermann, Paris, 1992.

[5] J. Li, Hilbert’s 16th problem and bifurcations of planar polynomial vector fields. Int. J.
Bifurcations & Chaos 13, 47–106, 2003.

[6] N. N. Bautin, On the number of limit cycles which appear with the variation of coeffi-
cients from an equilibrium position of focus or center type. Mat. Sbornik (N.S.) 30(72),
181–196, 1952.

[7] I. S. Kukles, Necessary and sufficient conditions for the existence of center. Dokl. Akad.
Nauk 42, 160–163, 1944.

[8] J. Li and Z. Liu, Bifurcation set and limit cycles forming compound eyes in a perturbed
Hamiltonian system. Publications Mathematiques 35, 487–506, 1991.

[9] Y. Liu and J. Li, On the singularity values of complex autonomous differential systems.
Sci. China (Ser. A) 3, 2450–255, 1989.

[10] K. E. Malkin, Criteria for center of a differential equation. Volg. Matem. Sbornik 2,
87–91, 1964.

[11] P. Yu and M. Han, Twelve limit cycles in a cubic case of the 16th Hilbert problem. Int.
J. Bifurcation & Chaos 15(7), 2191–2205, 2005.

[12] P. Yu and M. Han, Small limit cycles bifurcating from fine focus points in cubic order
$Z_2$-equivariant vector fields. Chaos, Solitons & Fractals 24, 329–348, 2005.

[13] Y. Q. Ye, Some problems in the qualitative theory of ordinary differential equations. J.
Diff. Eqns. 46, 153–164, 1982.

[14] R. Roussarie, Bifurcation of planar vector fields and Hilbert’s 16th problem. Progress
in Mathematics 164, Birkhauser Verlag, Basel, 1998.

[15] R. Roussarie and D. Schlomiuk, On the geometric structure of the class of planar
quadratic differential systems. Qualitative Theory of Dynamical Systems 3, 93–122,
2002.
[16] L. S. Chen and M. S. Wang, The relative position, and the number, of limit cycles of a quadratic differential system. *Acta. Math. Sinica* **22**, 751–758, 1979.

[17] S. Shi, A concrete example of the existence of four limit cycles for plane quadratic systems. *Sci. Sinica* **23**, 153–158, 1980.

[18] V. I. Arnold, Loss of stability of self-oscillations close to resonance and versal deformations of equivariant vector fields. *Funct. Anal. Appl.* **11**, 85–92, 1977.

[19] M. Han, Bifurcation of limit cycles of planar systems. Handbook of Differential Equations, Ordinary Differential Equations, Vol. 3 (Eds. A. Canada, P. Drabek and A. Fonda), Elsevier, 2006.

[20] H. Żoładek, Quadratic systems with center and their perturbations. *J. Diff. Eqns.* **109**, 223–273, 1994.

[21] E. Horozov and I. D. Iliev, On the number of limit cycles in perturbations of quadratic Hamiltonian systems. *J. Diff. Eqns.* **113**, 198–224, 1994.

[22] L. Gavrilov, The infinitesimal 16th Hilbert problem in the quadratic case. *Inventiones Mathematicae* **143**, 449–497, 2001.

[23] F. Dumortier, C. Li and Z. Zhang, Unfolding of a quadratic integrable system with two centers and two unbounded heteroclinic loop. *J. Diff. Eqns.* **139**, 146–193, 1997.

[24] L. Peng, Unfolding of a quadratic integrable system with a homoclinic loop. *Acta Math. Sinica* **18**, 737–754, 2002.

[25] J. Yu and C. Z. Li, Bifurcation of a class of planar non-Hamiltonian integrable systems with one center and one homoclinic loop. *J. Math. Anal. Appl.* **269**, 227–243, 2002.

[26] I. D. Iliev, C. Z. Li and J. Yu, Bifurcation of limit cycles from quadratic non-Hamiltonian systems with two centers and two unbounded heteroclinic loops. *Nonlinearity* **18**, 305–330, 2005.

[27] C. Li and J. Llibre, Quadratic perturbations of a quadratic reversible Lotka-Volterra system. Scientific Commons, 2006.

[28] P. G. Zhang, On the distribution and number of limit cycles for quadratic systems with two foci. *Qualitative Theory of Dynamical Systems* **3**, 437–463, 2002.

[29] P. Yu, Computation of normal forms via a perturbation technique. *J. Sound and Vib.* **211**, 19–38, 1998.

[30] M. Han, Cyclicity of planar homoclinic loops and application to quadratic systems. *Sci. China (Ser. A)* **27**, 891–902, 1997.
[31] M. Han, On Hopf cyclicity of planar systems. J. Math. Anal. Appl. 245, 404–422, 2000.

[32] M. Han and J. Chen, The number of limit cycles bifurcating from a pair of homoclinic loops. Sci. China (Ser. A) 30, 401–414, 2000.

[33] M. Han, J. Yang and P. Yu, Hopf Bifurcations for near-Hamiltonian Systems. Int. J. Bifurcation and Chaos 20(3), 2010.