九次等变平面 Hamilton 向量场的一般形式*

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摘 要：利用旋转对称群理论，给出了九次等变 Hamilton 向量场在复坐标和直角坐标下的两种一般形式，为进一步研究该类向量场的各种动力学性质奠定了基础．

关键词：等变向量场；旋转对称群；一般形式
中图分类号：O175.13 **文献标识码**：A **文章编号**：0529-6579（2001）01-0020-04

等变平面 Hamilton 向量场在弹性力学、天体物理等许多领域内都有应用．由于其形式较简单直观并具有旋转对称性[1]，所以它是讨论分支理论的基础，并且往往成为研究多项式系统的极限环个数及其分支的出发点，成为研究 Hilbert 16 问题及弱 Hilbert 16 问题的基础．因此研究高次等变平面 Hamilton 向量场有其理论和应用价值．

李继彬、刘正荣给出了具有等变性质的平面五次 Hamilton 向量场的一般性质[2]，讨论了具有等变性质的平面五次 Hamilton 向量场的分支[3]．

考虑实平面微分系统：

$$\frac{dx}{dt} = P(x,y), \quad \frac{dy}{dt} = Q(x,y) \qquad (1)$$

P,Q 关于 x 和 y 足够光滑（或者是 x,y 的多项式）．

令 $z = x + iy, \bar{z} = x - iy$ 则（1）变成：

$$\frac{dz}{dt} = F(z,\bar{z}), \frac{d\bar{z}}{dt} = \overline{F(z,\bar{z})} \qquad (2)$$

其中，$F(z,\bar{z}) = P(u,v) + iQ(u,v), u = (z + \bar{z})/2, v = (z - z)/2i$．

显然，当 $q \geqslant m+1$ 时次数为 $m-1$ 的 z_q- 等变哈密尔顿系统是一个平凡的旋转不变系统．

定理 1 对平面九次 Hamilton 系统，非平凡 z_q- 等变向量场有如下形式：

① $q = 10$，

$$F(z,\bar{z}) = (b_1 + b_2|z|^2 + b_3|z|^4 + b_4|z|^6 + b_5|z|^8)zi + A_6\bar{z}^9$$

② $q = 9$，

$$F(z,\bar{z}) = (b_1 + b_2|z|^2 + b_3|z|^4 + b_4|z|^6 + b_5|z|^8)zi + A_6\bar{z}^8$$

③ $q = 8$，

$$F(z,\bar{z}) = (b_1 + b_2|z|^2 + b_3|z|^4 + b_4|z|^6 + b_5|z|^8)zi + (A_6 - 9\bar{A}_7|z|^2)\bar{z}^7 + A_7z^9$$

④ $q = 7$，

$$F(z,\bar{z}) = (b_1 + b_2|z|^2 + b_3|z|^4 + b_4|z|^6 + b_5|z|^8)zi + A_6z^8 + (A_7 - 8\bar{A}_6|z|^2)\bar{z}^6$$

⑤ $q = 6$，

$$F(z,\bar{z}) = (b_1 + b_2|z|^2 + b_3|z|^4 + b_4|z|^6 + b_5|z|^8)zi + (A_6 + A_7|z|^2)z^7 + (A_8 - 7\bar{A}_6|z|^2 - 4\bar{A}_7|z|^4)\bar{z}^5$$

⑥ $q = 5$，

$$F(z,\bar{z}) = (b_1 + b_2|z|^2 + b_3|z|^4 + b_4|z|^6 + b_5|z|^8)zi + (A_6 + A_7|z|^2)z^6 + (A_8 - 6\bar{A}_6|z|^2 - 7/2\bar{A}_7|z|^4)\bar{z}^4 + A_9\bar{z}^9$$

⑦ $q = 4$，

$$F(z,\bar{z}) = (b_1 + b_2|z|^2 + b_3|z|^4 + b_4|z|^6 + b_5|z|^8)zi + (A_6 + A_7|z|^2 + A_8|z|^4)z^5 + A_9z^9 + (A_{10} - 5\bar{A}_6|z|^2 - 3\bar{A}_7|z|^4 - 7/3\bar{A}_8|z|^6)\bar{z}^3 + (A_{11} - 9\bar{A}_9|z|^2)\bar{z}^7$$

⑧ $q = 3$，

$$F(z,\bar{z}) = (b_1 + b_2|z|^2 + b_3|z|^4 + b_4|z|^6 + b_5|z|^8)zi + (A_6 + A_7|z|^2 + A_8|z|^4)z^4 + (A_9 + A_{10}|z|^2)z^7 + (A_{11} - 4\bar{A}_6|z|^2 - 5/2\bar{A}_7|z|^4 - 2\bar{A}_8|z|^6)\bar{z}^2 + (A_{12} - 7\bar{A}_9|z|^2 - 4\bar{A}_{10}|z|^4)\bar{z}^5 + A_{13}\bar{z}^8$$

⑨ $q = 2$，

$$F(z,\bar{z}) = (b_1 + b_2|z|^2 + b_3|z|^4 + b_4|z|^6 + b_5|z|^8)zi + (A_6 + A_7|z|^2 + A_8$$

* 收稿日期：2000-04-17；作者简介：杨利军（1973-），男，博士生．

$$|z|^4+A_9|z|^6)z^3+(A_{10}+A_{11}|z|^2+A_{12}|z|^4)z^5+(A_{13}+A_{14}|z|^2)z^7+A_{15}z^9+(A_{16}-3\bar{A}_6|z|^2-2\bar{A}_7|z|^4-5/3\bar{A}_8|z|^6-3/2\bar{A}_9|z|^8)\bar{z}+(A_{17}-5\bar{A}_{10}|z|^2-3\bar{A}_{11}|z|^4-7/3\bar{A}_{12}|z|^6)\bar{z}^3+(A_{18}-7\bar{A}_{13}|z|^2-4\bar{A}_{14}|z|^4)\bar{z}^5+(A_{19}-9\bar{A}_{15}|z|^2)\bar{z}^7+A_{20}\bar{z}^9$$

其中，b_j 为实数，A_j 为复数．

证明 由文[3]可知：由(2)式定义的向量场是 z_q- 等变的当且仅当函数 $F(z,\bar{z})$ 有如下形式

$$F(z,\bar{z})=\sum_{l=1}g_l(|z|^2)\bar{z}^{lq-1}+\sum_{l=0}h_l(|z|^2)z^{lq+1} \quad (3)$$

其中，$g_l(u)$，$h_l(u)$ 是 u 的复系数多项式．进一步，由（2）式定义的向量场是 z_q －等变哈密尔顿的当且仅当下式成立：

$$\frac{\partial F}{\partial z}+\frac{\partial\bar{F}}{\partial\bar{z}}\equiv 0 \quad (4)$$

由（2）式定义的向量场是 z_q －等变的当且仅当函数 $F(z,\bar{z})$ 有方程（3）的形式，并且函数 g_l 和 h_l 的所有系数是实数．

由复数的性质，定理得证．

定理 2 在直角坐标下，具有等变性质的九次 Hamilton 向量场的一般形式如下：

(1) $q=10$

$$\frac{dx}{dt}=-y[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(9x^8y-84x^6y^3+126x^4y^5-36x^2y^7+y^9)+a_6(9xy^8-84x^3y^6+126x^5y^4-36x^7y^2+x^9)$$

$$\frac{dy}{dt}=x[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(9xy^8-84x^3y^6+126x^5y^4-36x^7y^2+x^9)+a_6(-9x^8y+84x^6y^3-126x^4y^5+36x^2y^7-y^9)$$

(2) $q=9$

$$\frac{dx}{dt}=-y[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_6(x^2+y^2)^4]+b_6(8x^7y-56x^5y^3+56x^3y^5-8xy^7)+a_6(x^8-28x^6y^2+70x^4y^4-28x^2y^6+y^8)$$

$$\frac{dy}{dt}=x[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(x^8-28x^6y^2+70x^4y^4-28x^2y^6+y^8)+a_6(8xy^7-56x^3y^5+56x^5y^3-8x^7y)$$

(3) $q=8$

$$\frac{dx}{dt}=-y[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(21x^2y^5-35x^4y^3+7x^6y-y^7)+a_6(-7xy^6+35x^3y^4-21x^5y^2+x^7)+b_7(54x^8y-168x^6y^3-252x^4y^5+216x^2y^7-10y^9)+a_7(-8x^9+144x^7y^2-336x^3y^6+72xy^8)$$

$$\frac{dy}{dt}=x[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(x^7-21x^5y^2+35x^3y^4-7xy^6)+a_6(-7x^6y+35x^4y^3-21x^2y^5+y^7)+b_7(10x^9-216x^7y^2+252x^5y^4+168x^3y^6-54xy^8)+a_7(-8y^9+144x^2y^7-336x^6y^3+72x^8y)$$

(4) $q=7$

$$\frac{dx}{dt}=-y[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(40x^7y-56x^5y^3-168x^3y^5+56xy^7)+a_6(-7x^8+84x^6y^2+70x^4y^4-140x^2y^6+9y^8)+b_7(6x^5y-20x^3y^3+6xy^5)+a_7(x^6-15x^4y^2+15x^2y^4-y^6)$$

$$\frac{dy}{dt}=x[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(9x^8-140x^6y^2+70x^4y^4+84x^2y^6-7y^8)+a_6(56x^7y-168x^5y^3-56x^3y^5+40xy^7)+b_7(x^6-15x^4y^2+15x^2y^4-y^6)+a_7(-6x^5y+20x^3y^3-6xy^5)$$

(5) $q=6$

$$\frac{dx}{dt}=-y[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(8y^7-84x^2y^5+28x^6y)+a_6(-6x^7+42x^5y^2+70x^3y^4-42xy^6)+b_7(13x^8y+28x^6y^3-42x^4y^5-52x^2y^7+5y^9)+a_7(-3x^9+12x^7y^2+70x^5y^4+28x^3y^6-27xy^7)+b_8(y^5-10x^2y^3+5x^4y)+a_8(x^5-10x^3y^2+5xy^4)$$

$$\frac{dy}{dt}=x[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(8x^7-84x^5y^2+28xy^6)+a_6(6y^7-42x^2y^5-70x^4y^3+42x^6y)+b_7(5x^9-52x^7y^2-42x^5y^4+28x^3y^6+13xy^8)+a_7(3y^9-12x^2y^7-70x^4y^5-28x^6y^3+27x^8y)+$$

$b_8(x^5-10x^3y^2+5xy^4)+a_8(-y^5-5x^4y+10x^2y^3)$

(6) $q=5$

$$\frac{dx}{dt}=-y[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(20x^3y^3+18x^5y-30xy^5)+a_6(-5x^6+15x^4y^2+45x^2y^4-7y^6)+b_7(8x^7y+28x^5y^3-20xy^7)+a_7(-5/2x^8+35x^4y^4+28x^2y^6-9/2y^8)+b_8(4x^3y-4xy^3)+a_8(x^4-6x^2y^2+y^4)+b_9(9x^8y-84x^6y^3+126x^4y^5-36x^2y^7+y^9)+a_9(x^9-36x^7y^2+126x^5y^4-84x^3y^6+9xy^8)$$

$$\frac{dy}{dt}=x[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(7x^6-45x^4y^2-15x^2y^4+5y^6)+a_6(30x^5y-20x^3y^3-18xy^5)+b_7(9/2x^8-28x^6y^2-35x^4y^4+5/2y^8)+a_7(20x^7y-28x^3y^5-8xy^7)+b_8(x^4-6x^2y^2+y^4)+a_8(-4x^3y+4xy^3)+b_9(x^9-36x^7y^2+125x^5y^4-84x^3y^6+9xy^8)+a_9(-9x^8y+84x^6y^3-126x^4y^5+36x^2y^7-y^9)$$

(7) $q=4$

$$\frac{dx}{dt}=-y[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(10x^4y+20x^2y^3-6y^5)+a_6(-4x^5+20xy^4)+b_7(4x^6y+20x^4y^3+12x^2y^5-4y^7)+a_7(-6x^5y^2+10x^3y^4+14xy^6-2x^7)+b_8(2x^8y+56/3x^6y^3+28x^4y^5+8x^2y^7-10/3y^9)+a_8(-\frac{4}{3}x^9-8x^7y^2+\frac{56}{3}x^3y^6+12xy^8)+b_9(54x^8y-168x^6y^3-252x^4y^5-216x^2y^7-10b_9y^9)+a_9(-8x^9+144x^7y^2-336x^3y^6+72xy^8)+b_{10}(3x^2y-y^3)+a_{10}(x^3-3xy^2)+b_{11}(7x^6y-35x^4y^3+21x^2y^5-y^7)+a_{11}(x^7-21x^5y^2+35x^3y^4-7xy^6)$$

$$\frac{dy}{dt}=x[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(6x^5-20x^3y^2-10xy^4)+a_6(20x^4y-4y^5)+b_7(4x^7-12x^5y^2-20x^3y^4-4xy^6)+a_7(14x^6y+10x^4y^3-6x^2y^5-2y^7)+b_8(10/3x^9-28x^5y^4-56/3x^3y^6-2xy^8-8x^7y^2)+a_8(12x^8y+\frac{56}{3}x^6y^3-8x^2y^7-4/3y^9)+b_9(10x^9-216x^7y^2+252x^5y^4+168x^3y^6-54xy^9)+a_9(72x^8y-336x^6y^3+144x^2y^7-8y^9)+b_{10}(x^3-3xy^2)+a_{10}(-3x^2y+y^3)+b_{11}(x^7-21x^5y^2+35x^3y^4-7xy^6)+a_{11}(-7x^6y+35x^4y-21x^2y^5+y^7)$$

(8) $q=3$

$$\frac{dx}{dt}=-y[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(4x^3y+12xy^3)+a_6(-3x^4-6x^2y^2+5y^4)+b_7(x^5y+10x^3y^3+9xy^5)+a_7(-3/2x^6-15/2x^4y^2-5/2x^2y^4+7/2y^6)+b_8(8x^5y^3+16x^3y^5+8xy^7)+a_8(-x^8-8x^6y^2+10x^4y^4+3y^8)+b_9(28x^6y-84x^2y^5+8y^7)+a_9(-6x^7+42x^5y^2+70x^3y^4-42xy^6)+b_{10}(13x^8y+28x^6y^3-42x^4y^5-52x^2y^7+5y^9)+a_{10}(-3x^9+12x^7y^2+70x^5y^4+28x^2y^6-27xy^8)+2b_{11}xy+a_{11}(x^2-y^2)+b_{12}(5x^4y-10x^2y^3+y^5)+a_{12}(x^5-10x^3y^2+5xy^4)+b_{13}(8x^7y-56x^5y^3+56x^3y^5-8xy^7)+a_{13}(x^8-28x^6y^2+70x^4y^4-28x^2y^6+y^8)$$

$$\frac{dy}{dt}=x[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+b_6(5x^4-6x^2y^2-3y^4)+a_6(12x^3y+4xy^3)+b_7(7/2x^6-5/2x^4y^2-15/2x^2y^4-3/2y^6)+a_7(9x^5y+10x^3y^3+xy^5)+b_8(3x^8-10x^4y^4-8x^2y^6-y^8)+a_8(8x^7y+16x^5y^3+8x^3y^5)+b_9(8x^7-84x^5y^2+28xy^6)+a_9(42x^6y-70x^4y^3-42x^2y^5+6y^7)+b_{10}(5x^9-52x^7y^2-42x^5y^4+28x^3y^6+13xy^8)+a_{10}(27x^8y-28x^6y^3-70x^4y^5-12x^2y^7+3y^9)+b_{11}(x^2-y^2)-2a_{11}xy-b_{12}(x^5-10x^3y^2+5xy^4)+a_{12}(-5x^4y+10x^2y^3-y^5)+b_{13}(x^8-28x^6y^2+70x^4y^4-28x^2y^6+y^8)+a_{13}(-8x^7y+56x^5y^3-56x^3y^5+8xy^7)$$

(9) $q=2$

$$\frac{dx}{dt}=-y[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+4b_6y^3+a_6(-2x^3-6xy^2)+b_7(-x^4y+2x^2y^3+3y^5)+a_7(-x^5-6x^3y^2-5xy^4)+b_8(-4/3x^6y+4x^2y^5+8/3y^7)+a_8(-2/3x^7-6x^5y^2-10x^3y^4-14/3xy^6)+b_9(-3/2x^8y-2x^6y^3+3x^4y^5+6x^2y^7+5/2y^9)+a_9(-1/2x^9-6x^7y^2-15x^5y^4-14x^3y^6-9/2xy^8)+b_{10}(10x^4y+20x^2y^3-6y^5)+a_{10}(-4x^5+20xy^4)+b_{11}(4x^6y+20x^4y^3+12x^2y^5-4y^7)+a_{11}(-2x^7-6x^5y^2+10x^3y^4+14xy^6)+b_{12}(2x^8y+56/3x^6y^3+28x^4y^5+8x^2y^7-10/3y^9)+a_{12}(-4/3x^9-8x^7y^2+56/3x^3y^6+12xy^8)+b_{13}(28x^6y-84x^2y^5+8y^7)+$$

$a_{13}(-6x^7+42x^5y^2+70x^3y^4-42xy^6)+b_{14}(13x^8y+28x^6y^3-42x^4y^5-52x^2y^7+5y^9)+a_{14}(-3x^9+12x^7y^2+70x^5y^4+28x^3y^6-27xy^8)+b_{15}(54x^8y-168x^6y^3-252x^4y^5+216x^2y^7-10y^9)+a_{15}(-8x^9+144x^7y^2-336x^3y^6+72xy^8)+b_{16}y+a_{16}x+b_{17}(3x^2y-y^3)+a_{17}(x^3-3xy^2)+b_{18}(5x^4y-10x^2y^3+y^5)+a_{18}(x^5-10x^3y^2+5xy^4)+b_{19}(-y^7+7x^6y-35x^4y^3+21x^2y^5)+a_{19}(x^7-21x^5y^2+35x^3y^4-7xy^6)+b_{20}(9x^8y-84x^6y^3+126x^4y^5-36x^2y^7+y^9)+a_{20}(x^9-36x^7y^2+126x^5y^4-84x^3y^6+9xy^8)$

$$\frac{dy}{dt}=x[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4]+4b_6x^3+a_6(2y^3+6x^2y)+b_7(3x^5+2x^3y^2-xy^4)+a_7(5x^4y+6x^2y^3+y^5)+b_8(8/3x^7+4x^5y^2-4/3xy^6)+a_8(14/3x^6y+10x^4y^3+6x^2y^5+2/3y^7)+b_9(5/2x^9+6x^7y^2+3x^5y^4-2x^3y^6-3/2xy^8)+a_9(9/2x^8y+14x^6y^3+15x^4y^5+6x^2y^7+1/2y^9)+b_{10}(6x^5-20x^3y^2-10xy^4)+a_{10}(20x^4y-4y^5)+b_{11}(4x^7-12x^5y^2-20x^3y^4-4xy^6)+a_{11}(14x^6y+10x^4y^3-6x^2y^5-2y^7)+b_{12}(10/3x^9-8x^7y^2-28x^5y^4-56/3x^3y^6-2xy^8)+a_{12}(12x^8y+56/3x^6y^3-8x^2y^7-4/3y^9)+b_{13}(8x^7-84x^5y^2+28xy^6)+a_{13}(42x^6y-70x^4y^3-42x^2y^5+6y^7)+b_{14}(5x^9-52x^7y^2-42x^5y^4+28x^3y^6+13xy^8)+a_{14}(27x^8y-28x^6y^3-70x^4y^5-12x^2y^7+3y^9)+b_{15}(10x^9-216x^7y^2+252x^5y^4+168x^3y^6-54xy^8)+a_{15}(72x^8y-336x^6y^3+144x^2y^7-8y^9)+b_{16}x-a_{16}y+b_{17}(x^3-3xy^2)+a_{17}(-3x^2y+y^3)+b_{18}(x^5-10x^3y^2+5xy^4)+a_{18}(-5x^4y+10x^2y^3-y^5)+b_{19}(x^7-21x^5y^2+35x^3y^4-7xy^6)+a_{19}(-7x^6y+35x^4y^3-21x^2y^5+y^7)+b_{20}(x^9-36x^7y^2+126x^5y^4-84x^3y^7+9xy^8)+a_{20}(-9x^8y+84x^6y^3-126x^4y^5+36x^2y^7-y^9)$$

证明　限于篇幅，本文只对 $q=10$ 时进行证明，其它情况可类似得到．

由定理 1 知，非平凡 z_{10} 等变平面九次 Hamilton 系统有如下形式：

$$F(z,\bar{z})=(b_1+b_2|z|^2+b_3|z|^4+b_4|z|^6+b_5|z|^8)zi+A_6\bar{z}^9$$

令 $z=x+yi$，$A_6=a_6+b_6i$（a_6，b_6 为实数）则上式可写为：

$$F(x,y)=F(z,\bar{z})=[b_1+b_2(x^2+y^2)+b_3(x^2+y^2)^2+b_4(x^2+y^2)^3+b_5(x^2+y^2)^4](x+yi)i+(a_6+b_6i)(x-yi)^9 \quad (5)$$

又由（2）式可得：

$$\begin{cases}\dot{x}=(F(z,\bar{z})+\overline{F(z,\bar{z})})/2\\ \dot{y}=(F(z,\bar{z})-\overline{F(z,\bar{z})})/2i\end{cases} \quad (6)$$

将（5）代入（6）中并进行化简即可得证．

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General Form of the Planar Nine Degree Equivariant Hamiltonian System

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Abstract: By using the theory of rotation symmetry group, the general form of nine-degree planar equivariant Hamiltonian vector field under Cartisan axis and complex axis is obtained.

Keywords: equivlent vector field; rotation symmetry group; general form