糖果包装机推糖机构的运动精度分析

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摘要：目的 研究糖果包装机推糖机构的尺寸参数误差对其运动精度的影响，对位置、速度、加速度进行分析，找到机构中影响运动精度的薄弱环节。**方法** 采用复数矢量法、微分法，在误差独立作用原理的基础上，对其曲柄摇杆与扇形齿轮机构进行误差分析。**结果** 推糖杆机构的位置、速度、加速度误差在一定的范围内波动较小、对动态性能影响较小，其中杆 4 及其倾斜角对该机构运动精度影响相对较大，通过对方案的计算进行误差补偿，减小其波动的幅值。**结论** 避免糖果包装机推糖机构的结构尺寸出现在波动较大的范围内，对存在的难以避免的误差进行补偿设计，以提高机构运动精度。

关键词： 糖果包装机；推糖机构；复数矢量法；运动精度

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Kinematic Accuracy of Candy Pusher of Candy Packaging Machine

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ABSTRACT: The work aims to research the influence of candy pusher's dimension parameter error of candy packaging machine on its kinematic accuracy, and analyze the position, velocity and acceleration to find out the weak link of the pusher that affects the kinematic accuracy. The complex vector method and the differential method were used to analyze the error of its crank rocker and the sector gear mechanism on the basis of the independent action principle of the error. The position, velocity and acceleration errors of candy pusher fluctuated to some extent and had little effect on the dynamic performance. Rod 4 and slant angle had a relatively significant impact on the kinematic accuracy of the pusher. The error compensation was made for the scheme through calculation to reduce its amplitude of fluctuation. The large fluctuation of candy pusher of candy packaging machine can be avoided and the compensation design can be made for the unavoidable errors incurred, so as to improve the kinematic accuracy of the pusher.

KEY WORDS: candy packaging machine; candy pusher; complex vector method; kinematic accuracy

机构运动精度分析是机构完成操作任务、实现高精度运行要求的重要保证，对机构工作效率和动态性能的影响较大，且能为改善设计质量及提高设计水平提供参考依据。包装机械中的铰链机构及组合机构有着广泛应用。例如，在糖果包装机推糖机构中采用了四杆机构和弧度型机构[1]，在食用菌培养基包装机抱合机构中采用了曲柄摇杆机构[2]，在包装机械制袋机的热封及切刀传动机构中采用了曲柄滑块机构和曲柄摇杆机构[3]；在纸箱印刷机的送纸机构中采用了曲柄摆动导杆机构[4]；在印刷机的下摆式前规机构中采用了凸轮机构和 2 套四杆机构[5]；在数控糖果包装机中采用了四杆机构[6]。文中针对糖果包装机推糖机构，采用复数矢量法[7]和微分法，在误差独立作用原理[8]的基础上，建立由四杆机构、扇形齿轮机构组成的组合机构的位移误差、速度误差和加速度误差[9—10]的数学模型，并针对具体机构进行仿真和统计分析。

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1 四杆机构的位移方程

糖果包装机推糖机构及其四杆机构见图 1，该机构由四杆机构和扇形齿轮机构组成组合机构，扇形齿轮与四杆机构 CD 杆固连在一起，四杆机构见图 1b。

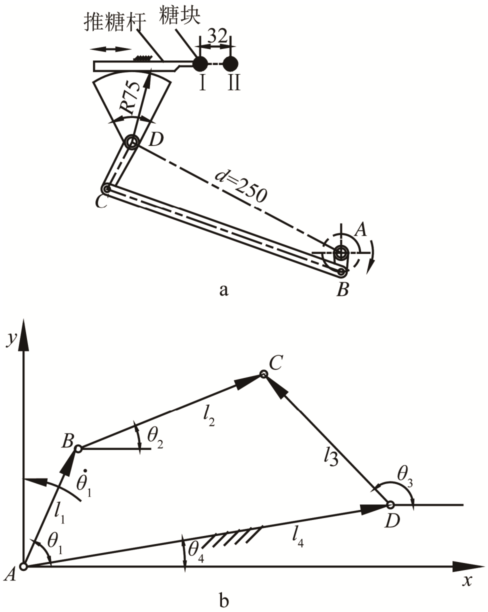

图 1 糖果包装机推糖机构及其四杆机构

Fig.1 Sugar pushing mechanism and four bar mechanism of candy packing machine

首先建立四杆机构的位移、速度和加速度误差模型，利用该组合机构特点，考虑扇形齿轮传动误差，建立推糖机构推杆位移、速度和加速度误差分析模型。常用的机构误差分析方法有微分法、矩阵法、微小位移合成法、转换机构法等[10]，文中采用复数矢量法对机构的误差进行分析[11]。由于四杆机构可构成封闭的机构，所以写成复数矢量的形式[12]：

$$l_1 e^{i\theta_1} + l_2 e^{i\theta_2} = l_3 e^{i\theta_3} + l_4 e^{i\theta_4} \tag{1}$$

应用欧拉公式 $e^{i\theta}=\cos\theta+i\sin\theta$，将式(1)分离实部和虚部，可得：

$$\begin{aligned} &l_1\cos\theta_1 + l_2\cos\theta_2 = l_3\cos\theta_3 + l_4\cos\theta_4 \\ &l_1\sin\theta_1 + l_2\sin\theta_2 = l_3\sin\theta_3 + l_4\sin\theta_4 \end{aligned} \tag{2}$$

式中：θ_1，θ_4 分别为输入值和给定的固定值；i 为一个虚数单位。求解 θ_2，θ_3 可得:

$$\begin{aligned} &\theta_2 = 2\arctan\left(\frac{A-\sqrt{A^2+B^2-C^2}}{B+C}\right), A=2l_2(l_1\sin\theta_1 - l_4\sin\theta_4), \\ &B=2l_2(l_1\cos\theta_1 - l_4\cos\theta_4), C=l_3^2-l_1^2-l_2^2-l_4^2+ \\ &\quad 2l_1l_4\cos(\theta_1-\theta_4) \\ &\theta_3 = 2\arctan\left(\frac{a-\sqrt{a^2+b^2-c^2}}{b+c}\right), a=2l_3(l_4\sin\theta_4 - l_1\sin\theta_1), \\ &b=2l_3(l_4\cos\theta_4 - l_1\cos\theta_1), c=l_2^2-l_1^2-l_3^2-l_4^2+ \\ &\quad 2l_1l_4\cos(\theta_1-\theta_4) \end{aligned} \tag{3}$$

扇形齿轮齿条机构[13]的齿条输出位移方程为：

$$S = R\theta \tag{4}$$

式中：R 为扇形齿轮节圆半径；θ 为转动的弧度。

2 四杆机构及其输出机构的位置误差分析

对位置误差进行分析，首先根据复数矢量法写出位置方程，对各杆分别进行偏微分，从而由变化量进行代替叠加得到位移的总误差方程。

1）仅考虑 l_1 的误差Δl_1时，对式(2)关于 l_1 求导可得：

$$\begin{aligned} &\cos\theta_1 - l_2\frac{\partial\theta_2}{\partial l_1}\sin\theta_2 = -l_3\frac{\partial\theta_3}{\partial l_1}\sin\theta_3 \\ &\sin\theta_1 + l_2\frac{\partial\theta_2}{\partial l_1}\cos\theta_2 = l_3\frac{\partial\theta_3}{\partial l_1}\cos\theta_3 \end{aligned} \tag{5}$$

求解可得：

$$\begin{aligned} &\frac{\partial\theta_2}{\partial l_1} = \frac{\cos(\theta_1-\theta_3)}{l_2\sin(\theta_2-\theta_3)} \\ &\frac{\partial\theta_3}{\partial l_1} = \frac{\cos(\theta_1-\theta_2)}{l_3\sin(\theta_2-\theta_3)} \end{aligned} \tag{6}$$

将 ∂l_1，$\partial\theta_2$，$\partial\theta_3$ 用Δl_1，$\Delta\theta_2$，$\Delta\theta_3$ 代替，则可得：

$$\begin{aligned} &\Delta\theta_{21} = f_{21}\cdot\Delta l_1 \\ &\Delta\theta_{31} = f_{31}\cdot\Delta l_1 \end{aligned} \tag{7}$$

式中：$f_{21}=\frac{\cos(\theta_1-\theta_3)}{l_2\sin(\theta_2-\theta_3)}$；$f_{31}=\frac{\cos(\theta_1-\theta_2)}{l_3\sin(\theta_2-\theta_3)}$；$\theta_{21}$ 和 θ_{31} 为受杆 1 影响时，杆 2 和杆 3 产生的误差；下文中出现的 θ_{ij}，$\dot{\theta}_{ij}$，α_{ij} 为受杆 j 影响时，杆 i 产生的误差；$\theta_{ij'}$，$\dot{\theta}_{ij'}$，$\alpha_{ij'}$为受倾角 θ_4 影响时，杆 i 产生的误差。

2）仅考虑 l_2 的误差Δl_2时，式(2)关于 l_2 求偏导可得：

$$\begin{aligned} &\cos\theta_2 - l_2\frac{\partial\theta_2}{\partial l_2}\sin\theta_2 = -l_3\frac{\partial\theta_3}{\partial l_2}\sin\theta_3 \\ &\sin\theta_2 + l_2\frac{\partial\theta_2}{\partial l_2}\cos\theta_2 = l_3\frac{\partial\theta_3}{\partial l_2}\cos\theta_3 \end{aligned} \tag{8}$$

求解可得：

$$\begin{aligned} &\frac{\partial\theta_2}{\partial l_2} = \frac{\cos(\theta_3-\theta_2)}{l_2\sin(\theta_2-\theta_3)} \\ &\frac{\partial\theta_3}{\partial l_2} = \frac{1}{l_3\sin(\theta_2-\theta_3)} \end{aligned} \tag{9}$$

同理，将 ∂l_2，$\partial\theta_2$，$\partial\theta_3$ 用 Δl_2，$\Delta\theta_2$，$\Delta\theta_3$ 代替，则：

$$\begin{aligned} &\Delta\theta_{22} = f_{22}\cdot\Delta l_2 \\ &\Delta\theta_{32} = f_{32}\cdot\Delta l_2 \end{aligned} \tag{10}$$

式中：$f_{22}=\frac{\cos(\theta_3-\theta_2)}{l_2\sin(\theta_2-\theta_3)}$；$f_{32}=\frac{1}{l_3\sin(\theta_2-\theta_3)}$。

3）仅考虑 l_3 的误差Δl_3时，式(2)关于 l_3 求偏导可得：

$$-l_2\frac{\partial\theta_2}{\partial l_3}\sin\theta_2=\cos\theta_3-\frac{\partial\theta_3}{\partial l_3}l_3\sin\theta_3$$
$$l_2\frac{\partial\theta_2}{\partial l_3}\cos\theta_2=\sin\theta_3+\frac{\partial\theta_3}{\partial l_3}l_3\cos\theta_3 \tag{11}$$

求解可得：

$$\frac{\partial\theta_2}{\partial l_3}=\frac{1}{l_2\sin(\theta_3-\theta_2)}$$
$$\frac{\partial\theta_3}{\partial l_3}=\frac{\cos(\theta_3-\theta_2)}{l_3\sin(\theta_3-\theta_2)} \tag{12}$$

同理，将 ∂l_3， $\partial\theta_2$， $\partial\theta_3$ 用 Δl_3，$\Delta\theta_2$，$\Delta\theta_3$ 代替，则：

$$\Delta\theta_{23}=f_{23}\cdot\Delta l_3$$
$$\Delta\theta_{33}=f_{33}\cdot\Delta l_3 \tag{13}$$

式中：$f_{23}=\dfrac{1}{l_2\sin(\theta_3-\theta_2)}$； $f_{33}=\dfrac{\cos(\theta_3-\theta_2)}{l_3\sin(\theta_3-\theta_2)}$。

4）仅考虑 l_4 的误差 Δl_4 时，式(2)关于 l_4 求偏导可得：

$$-\frac{\partial\theta_2}{\partial l_4}l_2\sin\theta_2=-\frac{\partial\theta_3}{\partial l_4}l_3\sin\theta_3+\cos\theta_4$$
$$l_2\frac{\partial\theta_2}{\partial l_4}\cos\theta_2=l_3\frac{\partial\theta_3}{\partial l_4}\cos\theta_3+\sin\theta_4 \tag{14}$$

求解可得：

$$\frac{\partial\theta_2}{\partial l_4}=\frac{\cos(\theta_3-\theta_4)}{l_2\sin(\theta_3-\theta_2)}$$
$$\frac{\partial\theta_3}{\partial l_4}=\frac{\cos(\theta_2-\theta_4)}{l_3\sin(\theta_3-\theta_2)} \tag{15}$$

同理，将 ∂l_4， $\partial\theta_2$， $\partial\theta_3$ 用 Δl_4，$\Delta\theta_2$，$\Delta\theta_3$ 代替，则：

$$\Delta\theta_{24}=f_{24}\cdot\Delta l_4$$
$$\Delta\theta_{34}=f_{34}\cdot\Delta l_4 \tag{16}$$

式中：$f_{24}=\dfrac{\cos(\theta_3-\theta_4)}{l_2\sin(\theta_3-\theta_2)}$； $f_{34}=\dfrac{\cos(\theta_2-\theta_4)}{l_3\sin(\theta_3-\theta_2)}$。

5）仅考虑 θ_4 的误差 $\Delta\theta_4$ 时，式(2)关于 θ_4 求偏导可得：

$$-l_2\frac{\partial\theta_2}{\partial\theta_4}\sin\theta_2=-l_3\frac{\partial\theta_3}{\partial\theta_4}\sin\theta_3-l_4\sin\theta_4$$
$$l_2\frac{\partial\theta_2}{\partial\theta_4}\cos\theta_2=l_3\frac{\partial\theta_3}{\partial\theta_4}\cos\theta_3+l_4\cos\theta_4 \tag{17}$$

求解可得：

$$\frac{\partial\theta_2}{\partial\theta_4}=\frac{l_4\sin(\theta_3-\theta_4)}{l_2\sin(\theta_3-\theta_2)}$$
$$\frac{\partial\theta_3}{\partial\theta_4}=\frac{l_4\sin(\theta_2-\theta_4)}{l_3\sin(\theta_3-\theta_2)} \tag{18}$$

同理，将 $\partial\theta_4$， $\partial\theta_2$， $\partial\theta_3$ 用 $\Delta\theta_4$，$\Delta\theta_2$，$\Delta\theta_3$ 代替，则：

$$\Delta\theta_{24'}=f_{24'}\cdot\Delta\theta_4$$
$$\Delta\theta_{34'}=f_{34'}\cdot\Delta\theta_4 \tag{19}$$

式中：$f_{24'}=\dfrac{l_4\sin(\theta_3-\theta_4)}{l_2\sin(\theta_3-\theta_2)}$； $f_{34'}=\dfrac{l_4\sin(\theta_2-\theta_4)}{l_3\sin(\theta_3-\theta_2)}$。

综上所述，铰链四杆机构[14]连杆和摇杆的角度误差为：

$$\Delta\theta_2=\Delta\theta_{21}+\Delta\theta_{22}+\Delta\theta_{23}+\Delta\theta_{24}+\Delta\theta_{24'}$$
$$\Delta\theta_3=\Delta\theta_{31}+\Delta\theta_{32}+\Delta\theta_{33}+\Delta\theta_{34}+\Delta\theta_{34'} \tag{20}$$

糖果包装机推糖机构扇形齿轮齿条机构的位置方程为：

$$S=R\theta_3 \tag{21}$$
$$R=r+e\cos\theta_3\cdot\cos\alpha \tag{22}$$

式中：R 为节圆实际半径；r 为节圆半径名义值；e 为齿轮径向综合误差；α=20°，为压力角。

糖果包装机推糖机构的位置误差方程为：

$$\Delta S=R\Delta\theta_3+e\sin\theta_3\cdot\cos\alpha \tag{23}$$

3　四杆机构的角速度误差的分析

将式(2)对时间 t 求导，可得角速度方程：

$$l_1\dot{\theta}_1\sin\theta_1+l_2\dot{\theta}_2\sin\theta_2=l_3\dot{\theta}_3\sin\theta_3$$
$$l_1\dot{\theta}_1\cos\theta_1+l_2\dot{\theta}_2\cos\theta_2=l_3\dot{\theta}_3\cos\theta_3 \tag{24}$$

求解可得连杆 l_2 和摇杆 l_3 的角速度为：

$$\dot{\theta}_2=\frac{l_1\dot{\theta}_1\sin(\theta_1-\theta_3)}{l_2\sin(\theta_3-\theta_2)}$$
$$\dot{\theta}_3=\frac{l_1\dot{\theta}_1\sin(\theta_1-\theta_2)}{l_3\sin(\theta_3-\theta_2)} \tag{25}$$

1）仅虑 l_1 的误差 Δl_1 时，由求位置误差的方法，将式(24)关于 l_1 求偏导，并进行求解可得：

$$\frac{\partial\dot{\theta}_2}{\partial l_1}=\frac{\dot{\theta}_1\sin(\theta_1-\theta_3)+l_2\dfrac{\partial\theta_2}{\partial l_1}\dot{\theta}_2\cos(\theta_2-\theta_3)-l_3\dfrac{\partial\theta_3}{\partial l_1}\dot{\theta}_3}{l_2\sin(\theta_3-\theta_2)}$$
$$\frac{\partial\dot{\theta}_3}{\partial l_1}=\frac{\dot{\theta}_1\sin(\theta_2-\theta_1)-l_2\dfrac{\partial\theta_2}{\partial l_1}\dot{\theta}_2+l_3\dfrac{\partial\theta_3}{\partial l_1}\dot{\theta}_3\cos(\theta_2-\theta_3)}{l_3\sin(\theta_2-\theta_3)} \tag{26}$$

将 $\partial\dot{\theta}_2$， $\partial\dot{\theta}_3$， ∂l_1 用 $\Delta\dot{\theta}_2$， $\Delta\dot{\theta}_3$， Δl_1 代替，则得到：

$$\Delta\dot{\theta}_{21}=v_{21}\cdot\Delta l_1$$
$$\Delta\dot{\theta}_{31}=v_{31}\cdot\Delta l_1 \tag{27}$$

式中：

$$v_{21}=\frac{\dot{\theta}_1\sin(\theta_1-\theta_3)+l_2\dfrac{\partial\theta_2}{\partial l_1}\dot{\theta}_2\cos(\theta_2-\theta_3)-l_3\dfrac{\partial\theta_3}{\partial l_1}\dot{\theta}_3}{l_2\sin(\theta_3-\theta_2)}；$$
$$v_{31}=\frac{\dot{\theta}_1\sin(\theta_2-\theta_1)-l_2\dfrac{\partial\theta_2}{\partial l_1}\dot{\theta}_2+l_3\dfrac{\partial\theta_3}{\partial l_1}\dot{\theta}_3\cos(\theta_2-\theta_3)}{l_3\sin(\theta_2-\theta_3)}。$$

2）仅考虑 l_2 的误差Δl_2时，同理，由求位置误差的方法，关于 l_2 求偏导，并进行求解可得：

$$\frac{\partial\dot{\theta}_2}{\partial l_2}=\frac{\dot{\theta}_2\sin(\theta_2-\theta_3)+l_2\dfrac{\partial\theta_2}{\partial l_2}\dot{\theta}_2\cos(\theta_2-\theta_3)-l_3\dfrac{\partial\theta_3}{\partial l_2}\dot{\theta}_3}{l_2\sin(\theta_3-\theta_2)}$$

$$\frac{\partial\dot{\theta}_3}{\partial l_2}=\frac{l_3\dfrac{\partial\theta_3}{\partial l_2}\dot{\theta}_3\cos(\theta_2-\theta_3)-l_2\dfrac{\partial\theta_2}{\partial l_2}\dot{\theta}_2}{l_3\sin(\theta_2-\theta_3)} \tag{28}$$

同理，将$\partial\dot{\theta}_2$，$\partial\dot{\theta}_3$，∂l_2用$\Delta\dot{\theta}_2$，$\Delta\dot{\theta}_3$，Δl_2代替，则：

$$\Delta\dot{\theta}_{22}=v_{22}\cdot\Delta l_2$$

$$\Delta\dot{\theta}_{32}=v_{32}\cdot\Delta l_2 \tag{29}$$

式中：

$$v_{22}=\frac{\dot{\theta}_2\sin(\theta_2-\theta_3)+l_2\dfrac{\partial\theta_2}{\partial l_2}\dot{\theta}_2\cos(\theta_2-\theta_3)-l_3\dfrac{\partial\theta_3}{\partial l_2}\dot{\theta}_3}{l_2\sin(\theta_3-\theta_2)};$$

$$v_{32}=\frac{l_3\dfrac{\partial\theta_3}{\partial l_2}\dot{\theta}_3\cos(\theta_2-\theta_3)-l_2\dfrac{\partial\theta_2}{\partial l_2}\dot{\theta}_2}{l_3\sin(\theta_2-\theta_3)}。$$

3）当仅考虑 l_3 的误差 Δl_3 时，同理，求解可得：

$$\frac{\partial\dot{\theta}_2}{\partial l_3}=\frac{l_2\dfrac{\partial\theta_2}{\partial l_3}\dot{\theta}_2\cos(\theta_2-\theta_3)-l_3\dfrac{\partial\theta_3}{\partial l_3}\dot{\theta}_3}{l_2\sin(\theta_3-\theta_2)}$$

$$\frac{\partial\dot{\theta}_3}{\partial l_3}=\frac{\dot{\theta}_3\sin(\theta_3-\theta_2)+l_3\dfrac{\partial\theta_3}{\partial l_3}\dot{\theta}_3\cos(\theta_3-\theta_2)-l_2\dfrac{\partial\theta_2}{\partial l_3}\dot{\theta}_2}{l_3\sin(\theta_2-\theta_3)} \tag{30}$$

将$\partial\dot{\theta}_2$，$\partial\dot{\theta}_3$，∂l_3用$\Delta\dot{\theta}_2$，$\Delta\dot{\theta}_3$，Δl_3代替，则：

$$\Delta\dot{\theta}_{23}=v_{23}\cdot\Delta l_3$$

$$\Delta\dot{\theta}_{33}=v_{33}\cdot\Delta l_3 \tag{31}$$

式中：$v_{23}=\dfrac{l_2\dfrac{\partial\theta_2}{\partial l_3}\dot{\theta}_2\cos(\theta_2-\theta_3)-l_3\dfrac{\partial\theta_3}{\partial l_3}\dot{\theta}_3}{l_2\sin(\theta_3-\theta_2)}$；$v_{33}=$

$$\frac{\dot{\theta}_3\sin(\theta_3-\theta_2)+l_3\dfrac{\partial\theta_3}{\partial l_3}\dot{\theta}_3\cos(\theta_3-\theta_2)-l_2\dfrac{\partial\theta_2}{\partial l_3}\dot{\theta}_2}{l_3\sin(\theta_2-\theta_3)}。$$

4）当仅考虑 l_4 的误差 Δl_4 时，同理，求解可得：

$$\frac{\partial\dot{\theta}_2}{\partial l_4}=\frac{l_2\dfrac{\partial\theta_2}{\partial l_4}\dot{\theta}_2\cos(\theta_2-\theta_3)-l_3\dfrac{\partial\theta_3}{\partial l_4}\dot{\theta}_3}{l_2\sin(\theta_3-\theta_2)}$$

$$\frac{\partial\dot{\theta}_3}{\partial l_4}=\frac{l_3\dfrac{\partial\theta_3}{\partial l_4}\dot{\theta}_3\cos(\theta_2-\theta_3)-l_2\dfrac{\partial\theta_2}{\partial l_4}\dot{\theta}_2}{l_3\sin(\theta_2-\theta_3)} \tag{32}$$

同理，将$\partial\dot{\theta}_2$，$\partial\dot{\theta}_3$，∂l_4用$\Delta\dot{\theta}_2$，$\Delta\dot{\theta}_3$，Δl_4代替，则：

$$\Delta\dot{\theta}_{24}=v_{24}\cdot\Delta l_4$$

$$\Delta\dot{\theta}_{34}=v_{34}\cdot\Delta l_4 \tag{33}$$

式中：$v_{24}=\dfrac{l_2\dfrac{\partial\theta_2}{\partial l_4}\dot{\theta}_2\cos(\theta_2-\theta_3)-l_3\dfrac{\partial\theta_3}{\partial l_4}\dot{\theta}_3}{l_2\sin(\theta_3-\theta_2)}$；$v_{34}=$

$$\frac{l_3\dfrac{\partial\theta_3}{\partial l_4}\dot{\theta}_3\cos(\theta_2-\theta_3)+l_2\dfrac{\partial\theta_2}{\partial l_4}\dot{\theta}_2}{l_3\sin(\theta_2-\theta_3)}。$$

5）仅考虑 θ_4 的误差 $\Delta\theta_4$ 时，同理，求解可得：

$$\frac{\partial\dot{\theta}_2}{\theta_4}=\frac{l_2\dfrac{\partial\theta_2}{\theta_4}\dot{\theta}_2\cos(\theta_2-\theta_3)-l_3\dfrac{\partial\theta_3}{\theta_4}\dot{\theta}_3}{l_2\sin(\theta_3-\theta_2)}$$

$$\frac{\partial\dot{\theta}_3}{\theta_4}=\frac{l_3\dfrac{\partial\theta_3}{\theta_4}\dot{\theta}_3\cos(\theta_2-\theta_3)-l_2\dfrac{\partial\theta_2}{\theta_4}\dot{\theta}_2}{l_3\sin(\theta_2-\theta_3)} \tag{34}$$

将$\partial\dot{\theta}_2$，$\partial\dot{\theta}_3$，$\partial\theta_4$用$\Delta\dot{\theta}_2$，$\Delta\dot{\theta}_3$，$\Delta\theta_4$代替，则：

$$\Delta\dot{\theta}_{24'}=v_{24'}\cdot\Delta\theta_4$$

$$\Delta\dot{\theta}_{34'}=v_{34'}\cdot\Delta\theta_4 \tag{35}$$

式中：$v_{24'}=\dfrac{l_2\dfrac{\partial\theta_2}{\partial l_4}\dot{\theta}_2\cos(\theta_2-\theta_3)-l_3\dfrac{\partial\theta_3}{\partial l_4}\dot{\theta}_3}{l_2\sin(\theta_3-\theta_2)}$；$v_{34'}=$

$$\frac{l_3\dfrac{\partial\theta_3}{\theta_4}\dot{\theta}_3\cos(\theta_2-\theta_3)-l_2\dfrac{\partial\theta_2}{\theta_4}\dot{\theta}_2}{l_3\sin(\theta_2-\theta_3)}。$$

综上所述，铰链四杆机构连杆和摇杆的角速度误差为：

$$\Delta\dot{\theta}_2=\Delta\dot{\theta}_{21}+\Delta\dot{\theta}_{22}+\Delta\dot{\theta}_{23}+\Delta\dot{\theta}_{24}+\Delta\dot{\theta}_{24'}$$

$$\Delta\dot{\theta}_3=\Delta\dot{\theta}_{31}+\Delta\dot{\theta}_{32}+\Delta\dot{\theta}_{33}+\Delta\dot{\theta}_{34}+\Delta\dot{\theta}_{34'} \tag{36}$$

糖果包装机推糖机构的速度方程为：

$$\dot{S}=\dot{R}\theta_3+R\dot{\theta}_3 \tag{37}$$

$$\dot{R}=-e\dot{\theta}_3\sin\theta_3\cos\alpha \tag{38}$$

糖果包装机推糖机构的速度误差方程为：

$$\Delta\dot{S}=\dot{R}\Delta\theta_3+R\Delta\dot{\theta}_3+e\dot{\theta}_3\cos\theta_3\cos\alpha \tag{39}$$

4 四杆机构的角加速度误差的分析

将速度公式对时间 t 求导，可得加速度公式[11]：

$$-l_1\dot{\theta}_1^2\sin\theta_1+l_2\alpha_2\cos\theta_2-l_2\dot{\theta}_2^2\sin\theta_2=l_3\alpha_3\cos\theta_3-l_3\dot{\theta}_3^2\sin\theta_3$$

$$l_1\dot{\theta}_1^2\cos\theta_1+l_2\alpha_2\sin\theta_2+l_2\dot{\theta}_2^2\cos\theta_2=l_3\alpha_3\sin\theta_3+l_3\dot{\theta}_3^2\cos\theta_3$$

$$\alpha_3=\frac{\dot{\theta}_1^{2}\,l_1\cos(\theta_1-\theta_2)+\dot{\theta}_2^{2}\,l_2-\dot{\theta}_3^{2}\,l_3\cos(\theta_3-\theta_2)}{l_3\sin(\theta_3-\theta_2)} \tag{40}$$

$$\alpha_2=\frac{-\dot{\theta}_1^{2}\,l_1\cos(\theta_1-\theta_3)-\dot{\theta}_2^{2}\,l_2\cos(\theta_2-\theta_3)+\dot{\theta}_3^{2}\,l_3}{l_3\sin(\theta_2-\theta_3)} \tag{41}$$

1）仅考虑 l_1 的误差 Δl_1 时，通过对加速度方程求偏导，解得：

$$\frac{\partial\alpha_2}{\partial l_1}=\frac{-\dot{\theta}_1^{2}\cos(\theta_1-\theta_3)-l_2\alpha_2\frac{\partial\theta_2}{\partial l_1}\cos(\theta_2-\theta_3)-2l_2\frac{\partial\dot{\theta}_2}{\partial l_1}\dot{\theta}_2\cos(\theta_2-\theta_3)+l_2\dot{\theta}_2^{2}\frac{\partial\theta_2}{\partial l_1}\sin(\theta_2-\theta_3)+l_3\alpha_3\frac{\partial\theta_3}{\partial l_1}+2l_3\frac{\partial\dot{\theta}_3}{\partial l_1}\dot{\theta}_3}{l_2\sin(\theta_2-\theta_3)}$$

$$\frac{\partial\alpha_3}{\partial l_1}=\frac{\dot{\theta}_1^{2}\cos(\theta_1-\theta_2)-l_3\frac{\partial\theta_3}{\partial l_1}\alpha_3\cos(\theta_2-\theta_3)-2l_3\frac{\partial\dot{\theta}_3}{\partial l_1}\dot{\theta}_3\cos(\theta_2-\theta_3)-l_3\frac{\partial\theta_3}{\partial l_1}\dot{\theta}_3^{2}\sin(\theta_3-\theta_2)+2l_2\frac{\partial\dot{\theta}_2}{\partial l_1}\dot{\theta}_2+l_2\alpha_2\frac{\partial\theta_2}{\partial l_1}}{l_3\sin(\theta_3-\theta_2)} \tag{42}$$

同理，将 $\partial\alpha_2$，$\partial\alpha_3$，∂l_1 用 $\Delta\alpha_2$，$\Delta\alpha_3$，Δl_1 代替，则：

$$\Delta\alpha_{21}=g_{21}\cdot\Delta l_1$$

$$\Delta\alpha_{31}=g_{31}\cdot\Delta l_1 \tag{43}$$

式中：

$$g_{21}=\frac{-\dot{\theta}_1^{2}\cos(\theta_1-\theta_3)-l_2\alpha_2\frac{\partial\theta_2}{\partial l_1}\cos(\theta_2-\theta_3)-2l_2\frac{\partial\dot{\theta}_2}{\partial l_1}\dot{\theta}_2\cos(\theta_2-\theta_3)+l_2\dot{\theta}_2^{2}\frac{\partial\theta_2}{\partial l_1}\sin(\theta_2-\theta_3)+l_3\alpha_3\frac{\partial\theta_3}{\partial l_1}+2l_3\frac{\partial\dot{\theta}_3}{\partial l_1}\dot{\theta}_3}{l_2\sin(\theta_2-\theta_3)};$$

$$g_{31}=\frac{\dot{\theta}_1^{2}\cos(\theta_1-\theta_2)-l_3\frac{\partial\theta_3}{\partial l_1}\alpha_3\cos(\theta_2-\theta_3)-2l_3\frac{\partial\dot{\theta}_3}{\partial l_1}\dot{\theta}_3\cos(\theta_2-\theta_3)-l_3\frac{\partial\theta_3}{\partial l_1}\dot{\theta}_3^{2}\sin(\theta_3-\theta_2)+2l_2\frac{\partial\dot{\theta}_2}{\partial l_1}\dot{\theta}_2+l_2\alpha_2\frac{\partial\theta_2}{\partial l_1}}{l_3\sin(\theta_3-\theta_2)}。$$

2）仅考虑 l_2 的误差 Δl_2 时，通过求偏导可得：

$$\frac{\partial\alpha_2}{\partial l_2}=\frac{\alpha_2\sin(\theta_3-\theta_2)-l_2\frac{\partial\theta_2}{\partial l_2}\alpha_2\cos(\theta_2-\theta_3)-\dot{\theta}_2^{2}\cos(\theta_2-\theta_3)-2l_2\frac{\partial\dot{\theta}_2}{\partial l_2}\dot{\theta}_2\cos(\theta_2-\theta_3)+l_2\frac{\partial\theta_2}{\partial l_2}\dot{\theta}_2^{2}\sin(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial l_2}\alpha_3+2l_3\frac{\partial\dot{\theta}_3}{\partial l_2}\dot{\theta}_3}{l_2\sin(\theta_2-\theta_3)}$$

$$\frac{\partial\alpha_3}{\partial l_2}=\frac{-l_3\frac{\partial\theta_3}{\partial l_2}\alpha_3\cos(\theta_2-\theta_3)-2l_3\frac{\partial\dot{\theta}_3}{\partial l_2}\dot{\theta}_3\cos(\theta_2-\theta_3)+l_3\dot{\theta}_3^{2}\frac{\partial\theta_3}{\partial l_2}\sin(\theta_3-\theta_2)+l_2\frac{\partial\theta_2}{\partial l_2}\alpha_2+\dot{\theta}_2^{2}+2l_2\frac{\partial\dot{\theta}_2}{\partial l_2}\dot{\theta}_2}{l_3\sin(\theta_3-\theta_2)} \tag{44}$$

同理，将 $\partial\alpha_2$，$\partial\alpha_3$，∂l_2 用 $\Delta\alpha_2$，$\Delta\alpha_3$，Δl_2 代替，则：

$$\Delta\alpha_{22}=g_{22}\cdot\Delta l_2$$

$$\Delta\alpha_{32}=g_{32}\cdot\Delta l_2 \tag{45}$$

式中：

$$g_{22}=\frac{\alpha_2\sin(\theta_3-\theta_2)-l_2\frac{\partial\theta_2}{\partial l_2}\alpha_2\cos(\theta_2-\theta_3)-\dot{\theta}_2^{2}\cos(\theta_2-\theta_3)-2l_2\frac{\partial\dot{\theta}_2}{\partial l_2}\dot{\theta}_2\cos(\theta_2-\theta_3)+l_2\frac{\partial\theta_2}{\partial l_2}\dot{\theta}_2^{2}\sin(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial l_2}\alpha_3+2l_3\frac{\partial\dot{\theta}_3}{\partial l_2}\dot{\theta}_3}{l_2\sin(\theta_2-\theta_3)}$$

$$;g_{32}=\frac{-l_3\frac{\partial\theta_3}{\partial l_2}\alpha_3\cos(\theta_2-\theta_3)-2l_3\frac{\partial\dot{\theta}_3}{\partial l_2}\dot{\theta}_3\cos(\theta_2-\theta_3)+l_3\dot{\theta}_3^{2}\frac{\partial\theta_3}{\partial l_2}\sin(\theta_3-\theta_2)+l_2\frac{\partial\theta_2}{\partial l_2}\alpha_2+\dot{\theta}_2^{2}+2l_2\frac{\partial\dot{\theta}_2}{\partial l_2}\dot{\theta}_2}{l_3\sin(\theta_3-\theta_2)}。$$

3）仅考虑 l_3 的误差 Δl_3 时，通过求偏导可得：

$$\frac{\partial\alpha_2}{\partial l_3}=\frac{-l_2\frac{\partial\theta_2}{\partial l_3}\alpha_2\cos(\theta_2-\theta_3)-2l_2\frac{\partial\dot{\theta}_2}{\partial l_3}\dot{\theta}_2\cos(\theta_2-\theta_3)+l_2\dot{\theta}_2^{2}\frac{\partial\theta_2}{\partial l_3}\sin(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial l_3}\alpha_3+2l_3\frac{\partial\dot{\theta}_3}{\partial l_3}\dot{\theta}_3+\dot{\theta}_3^{2}}{l_2\sin(\theta_3-\theta_2)}$$

$$\frac{\partial\alpha_3}{\partial l_3}=\frac{\alpha_3\sin(\theta_2-\theta_3)-l_3\frac{\partial\theta_3}{\partial l_3}\alpha_3\cos(\theta_2-\theta_3)-2l_3\frac{\partial\dot{\theta}_3}{\partial l_3}\dot{\theta}_3\cos(\theta_2-\theta_3)-\dot{\theta}_3^{2}\cos(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial l_3}\dot{\theta}_3^{2}\sin(\theta_3-\theta_2)+l_2\frac{\partial\theta_2}{\partial l_3}\alpha_2+2l_2\frac{\partial\dot{\theta}_2}{\partial l_3}\dot{\theta}_2}{l_3\sin(\theta_3-\theta_2)} \tag{46}$$

同理，将 $\partial\alpha_2$，$\partial\alpha_3$，∂l_3 用 $\Delta\alpha_2$，$\Delta\alpha_3$，Δl_3 代替，则：

$$\Delta\alpha_{23}=g_{23}\cdot\Delta l_3$$

$\Delta\alpha_{33}=g_{33}\cdot\Delta l_3$ (47)

式中：

$$g_{23}=\frac{-l_2\frac{\partial\theta_2}{\partial l_3}\alpha_2\cos(\theta_2-\theta_3)-2l_2\frac{\partial\dot\theta_2}{\partial l_3}\dot\theta_2\cos(\theta_2-\theta_3)+l_2\dot\theta_2^2\frac{\partial\theta_2}{\partial l_3}\sin(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial l_3}\alpha_3+2l_3\frac{\partial\dot\theta_3}{\partial l_3}\dot\theta_3+\dot\theta_3^2}{l_2\sin(\theta_3-\theta_2)};$$

$$g_{33}=\frac{\alpha_3\sin(\theta_2-\theta_3)-l_3\frac{\partial\theta_3}{\partial l_3}\alpha_3\cos(\theta_2-\theta_3)-2l_3\frac{\partial\dot\theta_3}{\partial l_3}\dot\theta_3\cos(\theta_2-\theta_3)-\dot\theta_3^2\cos(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial l_3}\dot\theta_3^2\sin(\theta_3-\theta_2)+l_2\frac{\partial\theta_2}{\partial l_3}\alpha_2+2l_2\frac{\partial\dot\theta_2}{\partial l_3}\dot\theta_2}{l_3\sin(\theta_3-\theta_2)}。$$

4）仅考虑 l_4 的误差 Δl_4 时，同理，求解可得：

$$\frac{\partial\alpha_2}{\partial l_4}=\frac{-l_2\frac{\partial\theta_2}{\partial l_4}\alpha_2\cos(\theta_2-\theta_3)-2l_2\frac{\partial\dot\theta_2}{\partial l_4}\dot\theta_2\cos(\theta_2-\theta_3)+l_2\frac{\partial\theta_2}{\partial l_4}\dot\theta_2^2\sin(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial l_4}\alpha_3+2l_3\frac{\partial\dot\theta_3}{\partial l_4}\dot\theta_3}{l_2\sin(\theta_2-\theta_3)}$$

$$\frac{\partial\alpha_3}{\partial l_4}=\frac{-l_3\frac{\partial\theta_3}{\partial l_4}\alpha_3\cos(\theta_2-\theta_3)-2l_3\frac{\partial\dot\theta_3}{\partial l_4}\dot\theta_3\cos(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial l_4}\dot\theta_3^2\sin(\theta_3-\theta_2)+l_2\frac{\partial\theta_2}{\partial l_4}\alpha_2+2l_2\frac{\partial\dot\theta_2}{\partial l_4}\dot\theta_2}{l_3\sin(\theta_3-\theta_2)}\quad(48)$$

同理，将 $\partial\alpha_2$，$\partial\alpha_3$，∂l_4 用 $\Delta\alpha_2$，$\Delta\alpha_3$，Δl_4 代替，则：

$\triangle\alpha_{24}=g_{24}\cdot\triangle l_4$

$\triangle\alpha_{34}=g_{34}\cdot\triangle l_4$ (49)

式中：

$$g_{24}=\frac{-l_2\frac{\partial\theta_2}{\partial l_4}\alpha_2\cos(\theta_2-\theta_3)-2l_2\frac{\partial\dot\theta_2}{\partial l_4}\dot\theta_2\cos(\theta_2-\theta_3)+l_2\frac{\partial\theta_2}{\partial l_4}\dot\theta_2^2\sin(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial l_4}\alpha_3+2l_3\frac{\partial\dot\theta_3}{\partial l_4}\dot\theta_3}{l_2\sin(\theta_2-\theta_3)};$$

$$g_{34}=\frac{-l_3\frac{\partial\theta_3}{\partial l_4}\alpha_3\cos(\theta_2-\theta_3)-2l_3\frac{\partial\dot\theta_3}{\partial l_4}\dot\theta_3\cos(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial l_4}\dot\theta_3^2\sin(\theta_3-\theta_2)+l_2\frac{\partial\theta_2}{\partial l_4}\alpha_2+2l_2\frac{\partial\dot\theta_2}{\partial l_4}\dot\theta_2}{l_3\sin(\theta_3-\theta_2)}。$$

5）仅考虑 θ_4 的误差 $\Delta\theta_4$ 时，求解可得：

$$\frac{\partial\alpha_2}{\partial\theta_4}=\frac{-l_2\frac{\partial\theta_2}{\partial\theta_4}\alpha_2\cos(\theta_2-\theta_3)-2l_2\frac{\partial\dot\theta_2}{\partial\theta_4}\dot\theta_2\cos(\theta_2-\theta_3)+l_2\frac{\partial\theta_2}{\partial\theta_4}\dot\theta_2^2\sin(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial\theta_4}\alpha_3+2l_3\frac{\partial\dot\theta_3}{\partial\theta_4}\dot\theta_3}{l_2\sin(\theta_2-\theta_3)}$$

$$\frac{\partial\alpha_3}{\partial\theta_4}=\frac{-l_3\frac{\partial\theta_3}{\partial\theta_4}\alpha_3\cos(\theta_2-\theta_3)-2l_3\frac{\partial\dot\theta_3}{\partial\theta_4}\dot\theta_3\cos(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial\theta_4}\dot\theta_3^2\sin(\theta_3-\theta_2)+l_2\frac{\partial\theta_2}{\partial\theta_4}\alpha_2+2l_2\frac{\partial\dot\theta_2}{\partial\theta_4}\dot\theta_2}{l_3\sin(\theta_3-\theta_2)}\quad(50)$$

同理，将 $\partial\alpha_2$，$\partial\alpha_3$，$\partial\theta_4$ 用 $\Delta\alpha_2$，$\Delta\alpha_3$，$\Delta\theta_4$ 代替，则：

$\Delta\alpha_{24'}=g_{24'}\cdot\Delta\theta_4$

$\Delta\alpha_{34'}=g_{34'}\cdot\Delta\theta_4$ (51)

式中：

$$g_{24'}=\frac{-l_2\frac{\partial\theta_2}{\partial\theta_4}\alpha_2\cos(\theta_2-\theta_3)-2l_2\frac{\partial\dot\theta_2}{\partial\theta_4}\dot\theta_2\cos(\theta_2-\theta_3)+l_2\frac{\partial\theta_2}{\partial\theta_4}\dot\theta_2^2\sin(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial\theta_4}\alpha_3+2l_3\frac{\partial\dot\theta_3}{\partial\theta_4}\dot\theta_3}{l_2\sin(\theta_2-\theta_3)};$$

$$g_{34'}=\frac{-l_3\frac{\partial\theta_3}{\partial\theta_4}\alpha_3\cos(\theta_2-\theta_3)-2l_3\frac{\partial\dot\theta_3}{\partial\theta_4}\dot\theta_3\cos(\theta_2-\theta_3)+l_3\frac{\partial\theta_3}{\partial\theta_4}\dot\theta_3^2\sin(\theta_3-\theta_2)+l_2\frac{\partial\theta_2}{\partial\theta_4}\alpha_2+2l_2\frac{\partial\dot\theta_2}{\partial\theta_4}\dot\theta_2}{l_3\sin(\theta_3-\theta_2)}。$$

综上所述，铰链四杆机构连杆和摇杆的角加速度误差为：

$$\Delta\alpha_2=\Delta\alpha_{21}+\Delta\alpha_{22}+\Delta\alpha_{23}+\Delta\alpha_{24}+\Delta\alpha_{24'}$$
$$\Delta\alpha_3=\Delta\alpha_{31}+\Delta\alpha_{32}+\Delta\alpha_{33}+\Delta\alpha_{34}+\Delta\alpha_{34'}\quad(52)$$

糖果包装机推糖机构的加速度方程为：

$$\ddot S=\ddot R\theta_3+2\dot R\dot\theta_3+R\ddot\theta_3\quad(53)$$

$$\ddot R=-e\dot\theta_3^2\cos\theta_3\cos\alpha\quad(54)$$

糖果包装机推糖机构的加速度误差方程为:

$$\Delta\ddot S=\ddot R\Delta\theta_3+2\dot R\Delta\dot\theta_3+R\Delta\ddot\theta_3-e(\dot\theta_3)^2\sin\theta_3\cos\alpha\quad(55)$$

5　推杆位移、速度和加速度误差的统计分析

推糖机构中四杆机构的输出杆 l_3 输出的位移误差、角速度误差和角加速度误差以及扇形齿轮齿条机构输出的线位移误差、线速度误差和线加速度误差都是随机过程，按随机过程理论对其进行统计特征分析[15]，可得均值方差方程：

$$
\begin{aligned}
&\mu(\Delta\theta_2)=E(\Delta\theta_{21}+\Delta\theta_{22}+\Delta\theta_{23}+\Delta\theta_{24}+\Delta\theta_{24'})\\
&\mu(\Delta\theta_3)=E(\Delta\theta_{31}+\Delta\theta_{32}+\Delta\theta_{33}+\Delta\theta_{34}+\Delta\theta_{34'})\\
&\sigma^2(\Delta\theta_2)=F(\Delta\theta_{21}+\Delta\theta_{22}+\Delta\theta_{23}+\Delta\theta_{24}+\Delta\theta_{24'})\\
&\sigma^2(\Delta\theta_3)=F(\Delta\theta_{31}+\Delta\theta_{32}+\Delta\theta_{33}+\Delta\theta_{34}+\Delta\theta_{34'})
\end{aligned}
\qquad (56)
$$

式中：μ，E，σ，F 分别代表均值、求解均值、方差、求解方差。四杆机构及推糖杆机构的速度误差和加速度误差的均值和方差的形式与式(56)相同，此处不再列出。

6　示例仿真分析

糖果包装机的推糖机构的结构参数[1]：l_1=20 mm，l_2=262 mm，l_3=56 mm，l_4=250 mm，θ_1=0°，r=75 mm，$\dot{\theta}_1$=1 rad/s。机构的结构尺寸精度根据 IT7 级进行设计，则各杆的尺寸参数误差为：Δl_1=0.3 mm，Δl_2=0.35 mm，Δl_3=0.3 mm，Δl_4=0.35 mm，$\Delta\theta_4$=0.5°，扇形齿轮径向综合公差按 6 级精度制造，由 GB 10095，e=36 μm，通过 Matlab 编程进行仿真分析的结果见图 2。

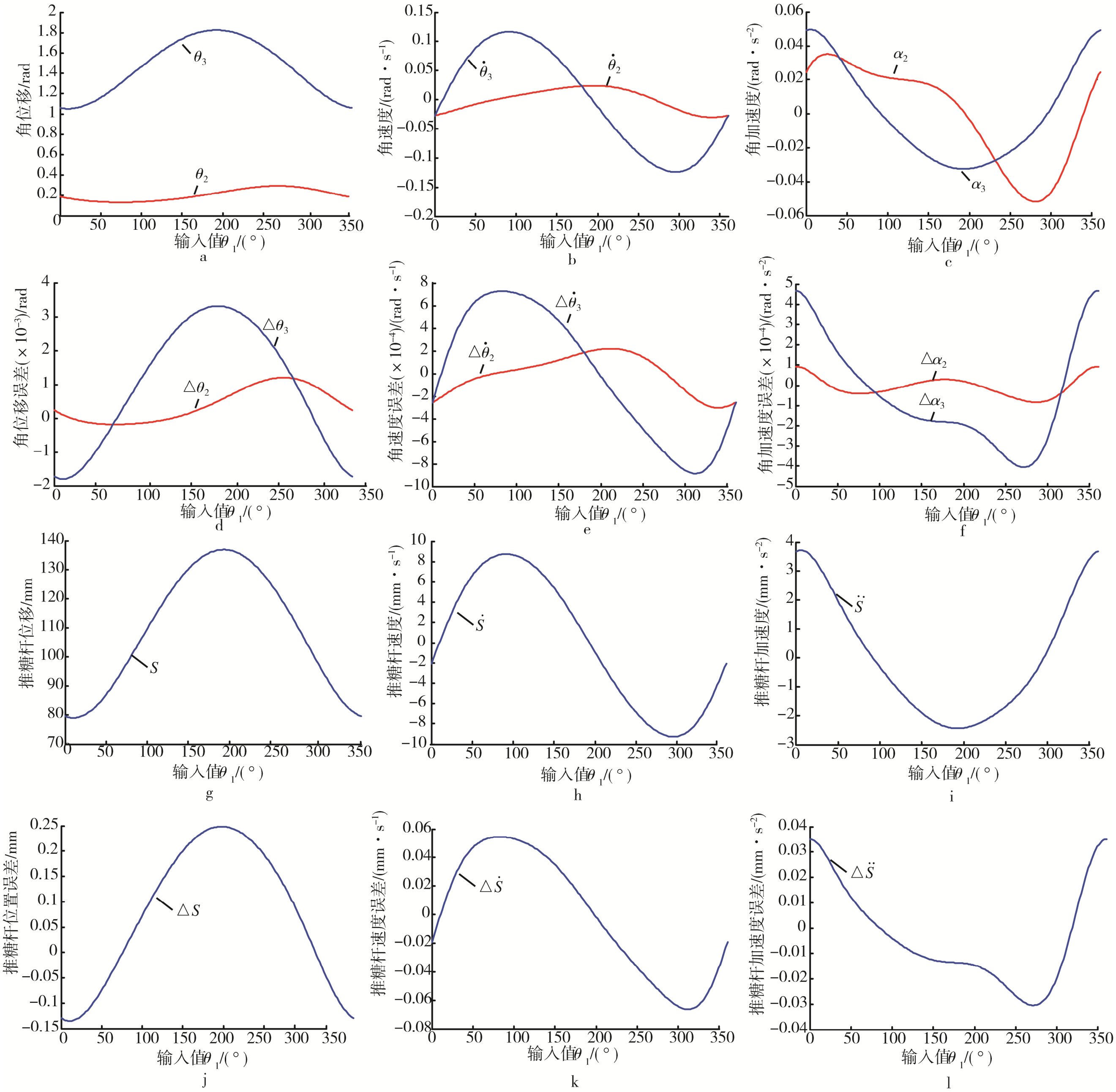

图 2　Matlab 仿真结果
Fig.2 Matlab simulation results chart

四杆机构杆 3 即扇形齿轮转动角位移、速度和加速度的值见图 2a—c，其误差见图 2d—f，推杆的位移、速度和加速度的值见图 2g—i，其误差见图 2j—l，在结构参数误差值给定的条件下，糖果包装机推糖机构的位置误差在曲柄转角 θ_1为 50°～100°和 300°～330°的角度范围内变化较小，其速度误差在 0°～20°和 190°～210°的范围内变动较小，动态性能影响较小，其加速度误差在 80°～100°和 300°～330°的范围内变动较小。任何构型下所对应的结构尺寸误差引起的机构位置、角速度和角加速度误差的均值和方差都可求得，求解结果见表 1。

分析表明，在该推糖杆机构的推杆运动误差分析中，θ_4 和 l_4 为对其影响最大的 2 个因素，为此，针对推杆误差的敏感因素提出误差补偿方法。以 A 为圆心，AD 的值为中性圆半径，在铰链 D 处机架上加工弧形槽，调整扇形齿轮齿条机构，无侧隙啮合。保持扇形齿轮齿条无侧隙啮合，减小往复运动的冲击，降低了对 θ_4 和 l_4 的精度要求。

表 1 糖果包装机输出机构尺寸误差的统计数字特征

Tab.1 The statistical characteristics of the dimension error of the output mechanism of candy packaging machine

	$\Delta\theta_2$/rad	$\Delta\theta_3$/rad	$\Delta\dot{\theta}_2$/(rad·s^{-1})	$\Delta\dot{\theta}_3$/(rad·s^{-1})	$\Delta\alpha_2$/(rad·s^{-2})	$\Delta\alpha_3$/(rad·s^{-2})	ΔS/mm	$\Delta\dot{S}$/(mm·s^{-1})	$\Delta\ddot{S}$/(mm·s^{-2})
均值	3.9505×10^{-4}	0.001	-1.2705×10^{-6}	-1.2705×10^{-6}	0.0011	0.0063	0.1337	0.2129	0.4734
方差	2.4582×10^{-7}	3.189×10^{-6}	2.7320×10^{-8}	3.2341×10^{-7}	1.1557×10^{-6}	3.9827×10^{-5}	0.0179	0.0453	0.2241

7 结语

利用复数矢量法和微分法，在误差独立作用原理的基础上，通过研究机构误差产生的随机过程以及数字的统计特征来对糖果包装机推糖机构的位移、速度和加速度的误差进行分析，可为机构的误差补偿及精度设计提供依据。文中方法可为其他包装机构的运动精度分析提供参考。

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