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# 平面折展机构 S 形柔性铰链设计与试验\*

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**摘要:** 设计平面折展柔顺机构的关键技术之一是设计柔性铰链。提出了一种用于平面折展柔顺机构的 S 形柔性铰链, 设计了该铰链的结构形式, 并对其等效刚度进行了分析, 推导出该结构形式铰链的弯曲等效刚度和扭转等效刚度计算公式。通过设计实例的理论计算和有限元仿真分析, 验证了计算公式和仿真模型的正确性。制作了基于 S 形柔性铰链的平面折展柔顺滑块机构的实物模型, 仿真分析和测试结果表明, 该机构在工作状态可具有较大变形, 并且滑块位移达到 76 mm 时仍能保持良好的精度, 仿真与测试结果基本一致, 误差仅为 0.76%。

**关键词:** 平面折展机构 S 形柔性铰链 等效刚度 平面折展滑块机构

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## 引言

柔顺机构是以柔性铰链代替传统机构运动关节, 以柔顺元件的弹性变形传递或转换运动和力的一种新型机构<sup>[1]</sup>。平面折展机构(Lamina emergent mechanisms, LEMs)是柔顺机构的一种, 由薄板材料加工制成, 可实现平面外运动<sup>[2]</sup>。具有减少构件数量和装配时间、简化加工工序、无摩擦磨损和运动副间隙, 以及降低振动和噪声等优点<sup>[3]</sup>。能实现四杆机构、滑块机构<sup>[4-5]</sup>、球面机构<sup>[6]</sup>、斯蒂芬森机构<sup>[7]</sup>等运动, 因此具有广泛的应用。如文献[8]用刚体替代法<sup>[9-10]</sup>设计多层 LEMs 水杯架, 文献[11-12]的 LEMs 升降台、卡片式 LEMs 注射器等。

柔顺机构的研究主要集中在柔性铰链上<sup>[13]</sup>。使用柔顺关节取代传统运动副, 从机构结构角度分析, 可使系统克服传统运动副所带来的一系列难题, 从根本上提高系统运行精度<sup>[14]</sup>。文献[7, 15]用不同形式的 LEMs 的铰链模拟刚性机构的转动副和移动副。文献[16-17]提出了 LET 铰链以及内 LET 铰链、外 LET 铰链, 推导了其等效刚度, 并且进行了有限元分析。文献[18]提出了适用于金属薄板的 TUFF 铰链和 RUFF 铰链。文献[19]提出了 I-LEJ 铰链、T-LEJ 铰链和 IT-LEJ 铰链, 这 3 种铰链在抗拉压方面的性能有所提高, 但弯曲性能有所下降。

本文提出一种新型柔性铰链, 使其具有较大的转动角度, 即弯曲等效刚度较小, 同时具有较小的变

形误差, 即较高的精度。

## 1 S 形柔性铰链设计

柔性铰链通过柔顺片段的弯曲或扭转来实现变形。单个柔顺片段大变形具有局限性, 易产生较大的应力, 也易发生塑性形变或疲劳断裂等。本文设计的 S 形柔性铰链通过多个柔顺片段的小变形累积来实现较大角位移。如图 1 所示, 根据铰链在转动变形过程中各部分所起的作用, 将铰链分成弯曲片段和扭转片段, 铰链的厚度为  $t$ , 总宽度为  $w_0$ , 总长度为  $l_0$ , 铰链  $x$  方向间隙为  $d$ 。

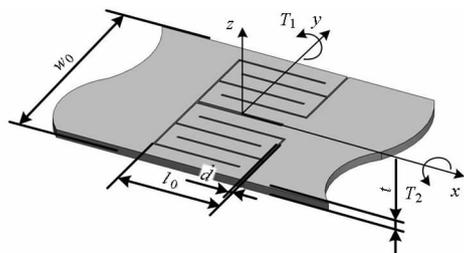


图 1 S 形柔性铰链的三维模型

Fig. 1 3D model of S-shaped flexure hinge

由于铰链关于  $x$  轴对称, 取铰链的二分之一作为研究对象。假设其二分之一部分有  $n$  个弯曲片段, 用  $b_i$  表示 ( $i=1, \dots, n$ ), 由铰链的结构可知其有  $n-1$  个扭转片段, 用  $t_j$  表示 ( $j=1, \dots, n-1$ ), 如图 2 所示。

除连接柔性杆件的弯曲片段  $b_n$  长度不同外, 其他各个弯曲和扭转片段完全相同。单个弯曲和扭转

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片段的尺寸示意如图3所示,取弯曲片段 $b_n$ 长度为 $l_{bn}$ ,宽度为 $w_b$ ,其余弯曲片段的长度为 $l_b$ ,宽度为 $w_b$ ,扭转片段的长度为 $l_t$ ,宽度为 $w_t$ 。根据几何关系,有 $l_{bn} = l_b + w_t + d$ ,  $l_0 = 2l_{bn} + 2d$ 。

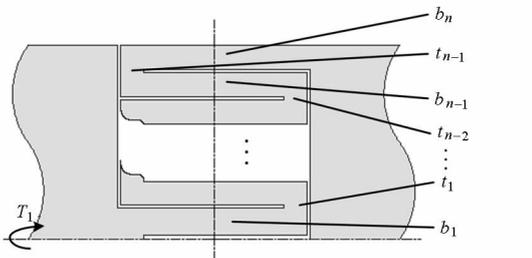


图2 n个弯曲片段的S形柔性铰链

Fig.2 S-shaped flexure hinge which has n bending segments

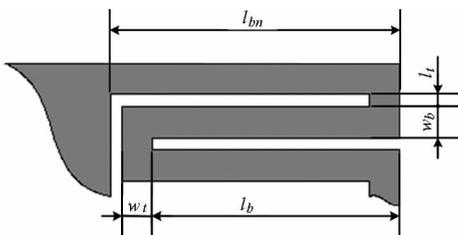


图3 S形柔性铰链弯曲时的弯扭片段尺寸示意图

Fig.3 Dimension labels for bending and torsion segments of S-shaped flexure hinge in bending condition

## 2 S形柔性铰链弯曲等效刚度分析

### 2.1 S形柔性铰链弯曲等效刚度

根据文献[16]的等效法,将扭转片段和弯曲片段分别等效为相应的扭转弹簧和弯曲弹簧,根据弹簧串并联等效关系,即可得出整个铰链的弯曲等效刚度 $k_{eq,bend}$ 。S形柔性铰链的弯曲等效弹簧模型如图4所示。

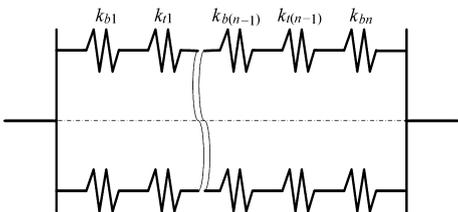


图4 S形柔性铰链的弯曲等效弹簧示意图

Fig.4 Associated bending spring model of S-shaped flexure hinge

根据弹簧的串并联关系,可以得出铰链转动时的等效弹簧刚度为

$$k_{eq,bend} = \frac{2}{\frac{1}{k_{b1}} + \frac{1}{k_{t1}} + \dots + \frac{1}{k_{b(n-1)}} + \frac{1}{k_{t(n-1)}} + \frac{1}{k_{bn}}} \quad (1)$$

由于扭转片段 $t_1, t_2, \dots, t_{n-1}$ 的形状完全相同,故其等效刚度也相同,记作 $k_t$ 。同理,弯曲片段 $b_1, b_2, \dots, b_{n-1}$ 的形状完全相同,故其等效刚度也相同,记作 $k_b$ 。代入式(1)化简后得

$$k_{eq,bend} = \frac{2}{\frac{n-1}{k_b} + \frac{n-1}{k_t} + \frac{1}{k_{bn}}} \quad (2)$$

其中

$$k_b = \frac{Ew_b t^3}{12l_b} \quad k_{bn} = \frac{Ew_b t^3}{12l_{bn}}$$

$$l_{bn} = l_b + w_t + d$$

$$k_t = w_t t^3 \frac{G}{l_t} \left[ \frac{1}{3} - 0.21 \frac{t}{w_t} \left( 1 - \frac{t^4}{12w_t^4} \right) \right]$$

式中  $G$ ——材料剪切模量

$E$ ——材料弹性模量

### 2.2 S形柔性铰链的实例设计

S形柔性铰链受到如图1所示 $y$ 轴方向的转矩 $T_1$ 时,有

$$T_1 = k_{eq,bend} \theta_1 \quad (3)$$

式中  $T_1$ ——作用在柔性铰链上的转矩

$\theta_1$ ——铰链的弯曲角度,rad

选取铍青铜作为S形柔性铰链的材料,其弹性模量 $E = 128 \text{ GPa}$ ,泊松比 $\sigma = 0.29$ ,屈服强度为 $[s_y] = 1170 \text{ MPa}$ 。选取铰链厚度 $t = 0.5 \text{ mm}$ ,铰链尺寸为 $25 \text{ mm} \times 50 \text{ mm}$ ,即铰链长度 $l_0 = 25 \text{ mm}$ ,铰链宽度 $w_0 = 50 \text{ mm}$ 。为避免铰链弯曲时铰链片段之间产生的干涉现象,选取 $d = 0.4 \text{ mm}$ 。

设计S形铰链旋转最大角度为 $\frac{\pi}{3}$ ,选取 $n = 5$ ,

此时每个弯曲扭转片段的最大转角为 $\frac{\pi}{15}$ ,铰链的弯曲扭转片段均发生较小的角位移。同时考虑到欲使铰链旋转时主要角位移发生在弯曲片段,取 $l_b = 22.2 \text{ mm}$ , $w_b = 4.5 \text{ mm}$ , $l_t = 0.5 \text{ mm}$ , $w_t = 3 \text{ mm}$ 。

将以上数据代入式(2)中,得 $k_{eq,bend} = 9.1589 \times 10^{-2} \text{ N}\cdot\text{m}/\text{rad}$ 。代入式(3),即可得到不同转矩下的弯曲角度,如表1所示。

表1 铰链转角仿真值、理论值及其误差

Tab.1 Comparison of bending rotation angle: theoretical calculation and finite element simulation analysis, together with the error

转矩/ (N·mm)	转角理论 值/rad	转角仿真 值/rad	相对 误差/%
10	0.1092	0.1093	0.09
20	0.2184	0.2186	0.12
30	0.3276	0.3280	0.11
40	0.4367	0.4372	0.11
50	0.5459	0.5465	0.11
60	0.6551	0.6557	0.09
70	0.7643	0.7649	0.08
80	0.8735	0.8741	0.07
90	0.9827	0.9832	0.05
100	1.0918	1.092	0.02

### 2.3 弯曲刚度的有限元仿真与验证

为验证理论计算的正确性,在 ABAQUS 中建立其有限元仿真模型,铰链转角为  $\frac{\pi}{3}$  时的变形如图 5 所示,应力云图如图 6 所示。由铰链的应力云图可知,此时铰链的最大应力为 532.7 MPa,约为许用应力  $[s_y] = 1\ 170\ \text{MPa}$  的一半,因而不会发生塑性变形,符合设计要求。

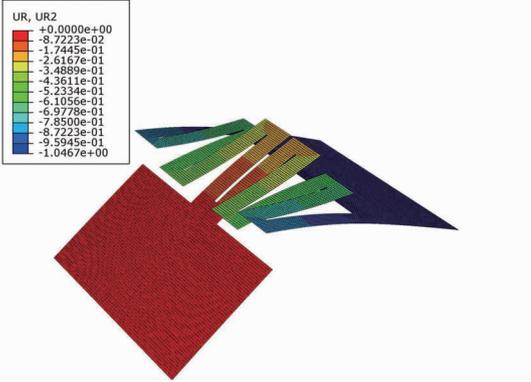


图 5 S 形柔性铰链弯曲时的角位移云图

Fig. 5 FEA model of the S-shaped flexure hinge showing the deflected position (radians) in bending condition

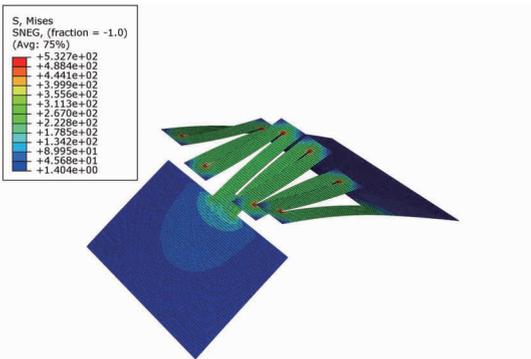


图 6 S 形柔性铰链弯曲时的应力云图

Fig. 6 FEA model of the S-shaped flexure hinge showing the stress in bending condition

分别对铰链施加不同的转矩,所得转角仿真值及其与理论计算值的相对误差如表 1 所示。

由表 1 可以看出,S 形柔性铰链在转矩作用下发生弯曲时,产生的转角与理论计算值基本一致。S 形柔性铰链的仿真刚度在铰链较大变形范围内基本不变,即转矩和转角具有良好的线性关系。在本实例中,仿真转角与理论转角的最大误差仅为 0.12%。

## 3 S 形柔性铰链扭转等效刚度分析

### 3.1 S 形柔性铰链扭转等效刚度

铰链受到如图 1 所示  $x$  轴方向上的转矩  $T_2$  时,会产生扭转变形,此时,图 1 中铰链的扭转片段变为弯曲片段,弯曲片段变为扭转片段,重新定义各段变

量如图 7 所示。

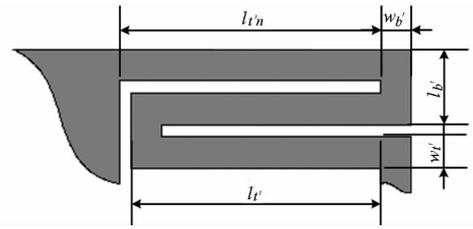


图 7 S 形柔性铰链扭转时的弯扭片段尺寸示意图

Fig. 7 Dimension labels for bending and torsion segments of S-shaped flexure hinge in torsion condition

同样,根据文献[16]的等效法,将扭转片段和弯曲片段分别等效为相应的扭转弹簧和弯曲弹簧,根据弹簧串并联等效关系,即可得出整个铰链的扭转等效刚度  $k_{eq,tors}$ 。S 形柔性铰链的扭转等效弹簧模型如图 8 所示。

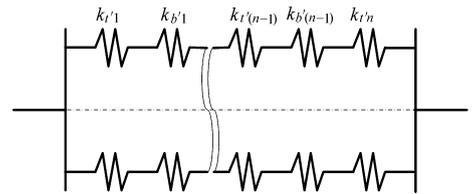


图 8 S 形柔性铰链的扭转等效弹簧示意图

Fig. 8 Associated torsion spring model of S-shaped flexure hinge

根据弹簧的串并联关系,可以得出铰链扭转时的等效弹簧刚度

$$k_{eq,tors} = \frac{2}{\frac{1}{k_{t'1}} + \frac{1}{k_{b'1}} + \dots + \frac{1}{k_{t'(n-1)}} + \frac{1}{k_{b'(n-1)}} + \frac{1}{k_{t'n}}} \quad (4)$$

由于扭转片段  $t'_1, t'_2, \dots, t'_{n-1}$  的形状完全相同,故其等效刚度也相同,记作  $k_{t'}$ 。同理,弯曲片段  $b'_1, b'_2, \dots, b'_{n-1}$  的形状完全相同,故其等效刚度也相同,记作  $k_{b'}$ 。代入公式(4)化简后得

$$k_{eq,bend} = \frac{2}{\frac{n-1}{k_{b'}} + \frac{n-1}{k_{t'}} + \frac{1}{k_{t'n}}} \quad (5)$$

其中

$$k_{b'} = \frac{Ew_b t^3}{12l_{b'}}$$

$$k_{t'} = w_t t^3 \frac{G}{l_{t'}} \left[ \frac{1}{3} - 0.21 \frac{t}{w_t} \left( 1 - \frac{t^4}{12w_t^4} \right) \right]$$

$$k_{t'n} = w_{t'n} t^3 \frac{G}{l_{t'n}} \left[ \frac{1}{3} - 0.21 \frac{t}{w_{t'n}} \left( 1 - \frac{t^4}{12w_{t'n}^4} \right) \right]$$

$$l_{t'n} = l_{t'} + w_{b'} + d$$

$$w_{b'} = w_t$$

$$l_{b'} = l_t + 2w_b$$

$$w_{t'} = w_b$$

$$l_{t'} = l_b$$

### 3.2 扭转刚度的有限元仿真与验证

S形柔性铰链受到如图1所示x轴方向的转矩 $T_2$ 时,有

$$T_2 = k_{eq, bend} \theta_2 \quad (6)$$

式中  $T_2$ ——作用在柔性铰链上的扭矩

$\theta_2$ ——铰链的扭转角度,rad

将2.2节设计实例代入式(5),得  $k_{eq, tors} = 9.798 \times 10^{-2} \text{ N}\cdot\text{m}/\text{rad}$ 。代入式(6),即可得到不同转矩下的扭转角度,如表2所示。

表2 铰链扭转角仿真值、理论值及其误差

Tab.2 Comparison of torsion angle: theoretical calculation and finite element simulation analysis, together with the error

转矩/ (N·mm)	扭转角理论 值/rad	扭转角仿真 值/rad	相对 误差/%
10	0.1107	0.1170	5.66
20	0.2215	0.2316	4.58
30	0.3322	0.3428	3.19
40	0.4429	0.4510	1.82
50	0.5536	0.5564	0.50
60	0.6644	0.6591	0.79
70	0.7751	0.7594	2.03
80	0.8858	0.8570	3.26
90	0.9966	0.9520	4.47
100	1.1073	1.0440	5.72

在仿真时对铰链施加x轴方向不同大小的扭矩,得到此时的转角大小如表2。铰链在0.03 N·m的转矩下的应力云图如图9所示。此时铰链的最大应力为532.4 MPa,约为许用应力 $[s_y] = 1170 \text{ MPa}$ 的一半,因而不会发生塑性变形,符合设计要求。

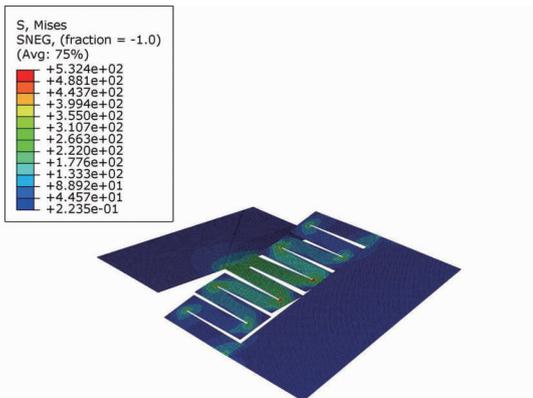


图9 铰链的扭转应力云图

Fig.9 FEA model of the S-shaped flexure hinge showing the stress in torsion condition

由分析可知,铰链发生扭转变形时,仿真转角与理论转角较接近,可以考虑将S形柔性铰链作为二自由度的铰链使用。或者通过结构优化增大铰链扭转刚度,以作为单自由度的铰链使用。

### 4 基于S形柔性铰链的平面折展机构

基于2.2节的设计实例,设计基于S形柔性铰链的平面折展柔顺滑块机构,经北京科技大学加工中心进行加工制造,选取与2.2节铰链相同材料铍青铜,采用线切割工艺进行加工而成的机构实物初始状态如图10所示,机构展开状态和铰链弯曲变形局部放大如图11所示。将S形铰链应用于滑块机构中,可以实现较大的滑块位移,滑块位移 $s_3$ 为76.2 mm时机构的实物图如图12所示,测得角度 $\alpha_1$ 为65.50°。同时建立机构有限元仿真模型如图13所示,仿真得到滑块位移 $s_3$ 为76.2 mm时角度 $\alpha_1$ 为65.55°。结果基本一致,因此S形柔性铰链能够实现预期的功能。



图10 平面折展滑块机构初始状态实物图

Fig.10 LEMs slider mechanism model of the S-shaped flexure hinge in original state

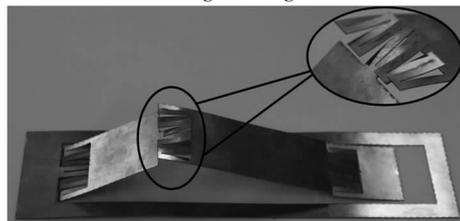


图11 平面折展滑块机构展开状态和铰链弯曲变形局部放大实物图

Fig.11 LEMs slider mechanism model in expanded state and magnification of the S-shaped flexure hinge



图12 平面折展滑块机构的展开状态实物主视图

Fig.12 LEMs slider mechanism model in its operating state

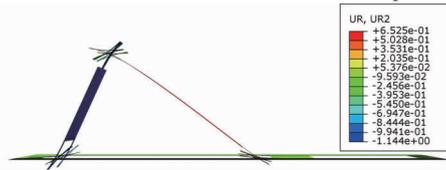


图13 平面折展滑块机构的运行仿真图

Fig.13 LEMs slider mechanism FEA model in its operating state

### 5 结论

(1) 设计了一种S形的柔性铰链结构,并对其

弯曲等效刚度进行了理论公式推导,通过有限元仿真分析,验证了公式的正确性。也验证了所设计实例能够满足设计要求,在许用应力范围内能够实现较大的转角,同时具有较小的误差。

(2) 对 S 形柔性铰链的扭转等效刚度进行了理论公式的推导,并进行有限元仿真,验证了公式的正确性。由于其较小的扭转等效刚度,故需进一步进

行研究,如通过优化设计来增大扭转刚度,也可以考虑作为二自由度的铰链用于实现复杂运动。

(3) 制作了基于 S 形柔性铰链的平面折展柔顺滑块机构的实物模型,测试结果表明 S 形柔性铰链能够实现预期的变形。该机构具有较大变形,并且在较大变形下仍能保持良好的精度,达到了设计目的。

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## Elasto-dynamics Optimal Design of Spatial Parallel Mechanism

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**Abstract:** The elasto-dynamics optimal design of 4-UPS-UPU 5-DOF spatial parallel mechanism was studied. The elasto-dynamic models of 4-UPS-UPU spatial parallel mechanism were established based on kineto-elasto dynamics. The total mass function and base frequency function of the parallel mechanism were integrated into a comprehensive optimization objective function, and the restrictive condition of the maximum deformation energy and the maximum dynamic stress of five driving limbs were considered as constraint equations to perform the optimal design. The optimized methods, such as fmincon function in matlab software and genetic algorithms were used respectively. The optimal parameters of the mass of moving platform and the sectional area of five driving limbs were determined based on the optimal design. And the correctness and rationality of the optimized method and results were verified.

**Key words:** Spatial parallel mechanism Elasto-dynamics Optimal design

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## Design and Test of Lamina Emergent Mechanisms S-shaped Flexure Hinge

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**Abstract:** Part of the challenge in designing LEMs (Lamina emergent mechanisms) comes in designing the suitable flexure hinges. A new S-shaped flexure hinge used on LEMs was proposed and its structure was designed. The bending stiffness equivalent and torsion stiffness equivalent of the S-shaped flexure hinge was presented. By theoretical calculation and finite element simulation analysis of the design example, the correctness of the calculation formula and simulation models was verified. The LEMs slider mechanism base on S-shaped flexure hinge was produced. The FEA model and test results prove that this mechanism can produce large deformation with high accuracy in operating state, when the displacement of slider reached to 76 mm, the FEA and test results are basically the same, the deviation between them is 0.76%.

**Key words:** LEMs S-shaped flexure hinge Equivalent stiffness LEMs slider mechanism