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快速反射镜两轴柔性支承设计

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摘要：

Φ90 mm ±2 mrad 300 Hz
dSPACE

78 Hz 340 Hz
mrad Hz

关 键 词：快速反射镜；柔性支承；柔性铰链；特性设计
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A new elastic support based on the lumped compliance of flexure hinges was presented for a two-axis Fast Steering Mirror FSM system and the methods to analyze the static and dynamic performance of the elastic support were researched. Firstly the principle of two-axis FSM and the performance demand of an elastic support were analyzed and the advantages and disadvantages of several existing elastic supports were researched. Then a new elastic support based on a right-corner flexure hinge structure was put forward and the static and dynamic performance of the new elastic support was studied in detail. By taking a designed two-axis FSM with the performance in Φ90 mm beam aperture ±2 mrad deflection angle and 300 Hz closed-loop bandwidth for an example the characteristics of the elastic support were analyzed and the rotational stiffness of the elastic support was measured based on the dSPACE simulation system. Experimental results indicate that the elastic support can meet the performance of FSM well and its first-order resonance frequency is 78 Hz and the close-loop bandwidth tested is 340 Hz. It is concluded that the two-axis elastic support based on the lumped compliance of flexure hinge structure can be used for the FSM which needs several mrad deflection an-

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gles and several hundred Hz close-loop bandwidths and it has advanteges in easy machining and a stable rotation center.

Fast Steering Mirror FSM elastic support flexure hinge performance design

引 言

Fast Steering Mirror system FSM

[1-4]

Left Hand Design Corporation LHDC National Aeronautics and Space Administration NASA Jet Propulsion Laboratory JPL Voice Coil Actuator VCA FSM Space Interferometry Mission SIM PI NEWPORT

Ball Aerospace Corporation MIT

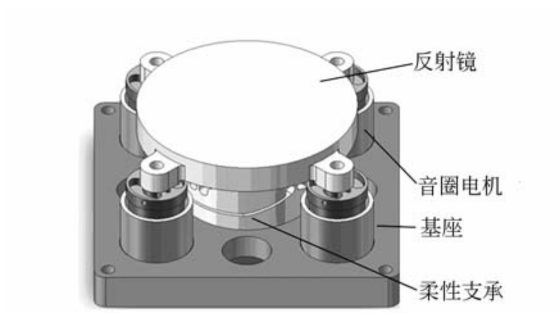
° 205

mrad Hz

两轴快速反射镜工作原理与柔性支承特性要求

. 快速反射镜工作原理

1



1

Fig. 1 Structure of a two-axis fast steering mirror system

. 柔性支承特性需求

FSM

FSM [5]

1 FSM

2 FSM

3

4

5

غ

FSM

基于柔性铰链单元的柔性支承设计

. 结构形式

ط

6-7 2 3

س

3

a b س c

a Flexure hinge b Flexure blade c Flexure shaft

2

Fig. 2 Several typical flexible elements

3

3 a MIT

3 b PI S-340

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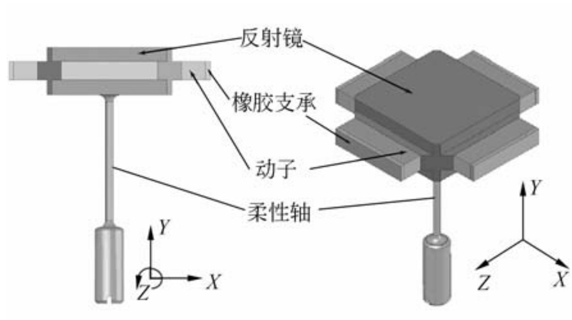

a MIT FSM

a FSM elastic support by MIT

b PI S-340 FSM

b S-340 FSM by PI Inc.

3

Fig. 3 Two elastic supports in existing FSMs

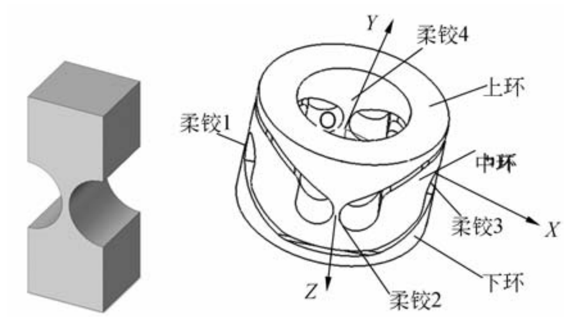

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Fig. 4 Right-corner flexure hinge and elastic support

1 3 X

2 4 Z

1 3

2 4 1 3

4

X Z

. 柔性铰链单元特性分析

$-\pi\ 2 \leqslant \alpha \leqslant \pi\ 2$

N

ش R $\mathrm{d}x$ $\alpha = t + 2R$

t b Z $K_{\theta Z}$ $-2R\cos\alpha$

[8-10]

5

M Z θ_z

$$\frac{1}{\rho\ x} = \frac{\mathrm{d}^2 \upsilon}{\mathrm{d}x^2} = \frac{M\ x}{EI_z\ x} \quad (1)$$

E $M\ x$

$I_Z\ x$ $\upsilon\ x$

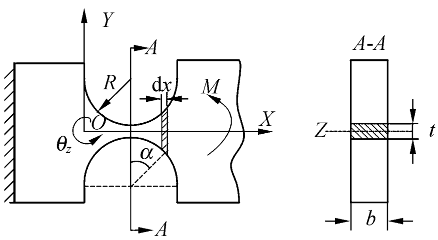

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Fig. 5 Shape force and deformation of flexure hinge

$$I_Z = \frac{ba^3}{12} = \frac{b\ t + 2R - 2R\cos\alpha\ ^3}{12} \quad (2)$$

Z θ_z

$$\theta_Z = \frac{\mathrm{d}\upsilon}{\mathrm{d}x} = \int \frac{M}{EI_Z\ x}\mathrm{d}x = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{12M\cos\alpha}{EbR^2\ \frac{t}{R} + 2 - \cos\alpha\ ^3}\mathrm{d}\alpha \quad (3)$$

Z

$$K_Z = \frac{M}{\theta_Z} = \frac{EbR^2}{12}\ \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{\cos\alpha}{\frac{t}{R} + 2 - \cos\alpha\ ^3}\mathrm{d}\alpha\ = EbR^2\ 12\ \frac{12s^4\ 2s+1}{4s+1\ ^{\frac{5}{2}}}\arctan\sqrt{4s+1} + \frac{2s^3\ 6s^2 + 4s + 1}{4s+1\ ^2\ 2s+1} \quad (4)$$

$s = R\ t.$

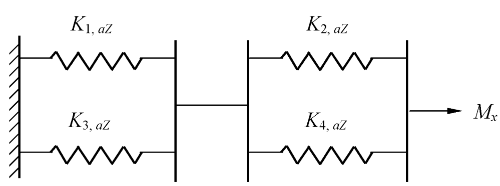
Z

ش R t b

[11]

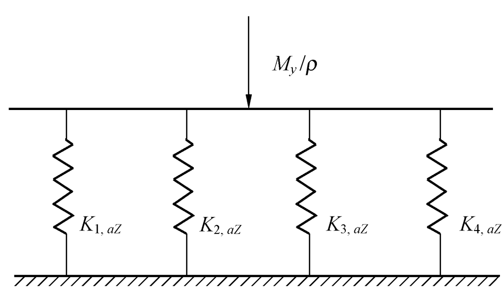
b ي $R\ t$ t

R b



a X

a Stiffness of rot. X



b Y

b Stiffness of rot. Y

6

Fig. 6 Stiffness relationship between elastic support and flexure hinge element

. 柔性支承与柔性铰链单元特性的关系

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. 柔性支承设计方法

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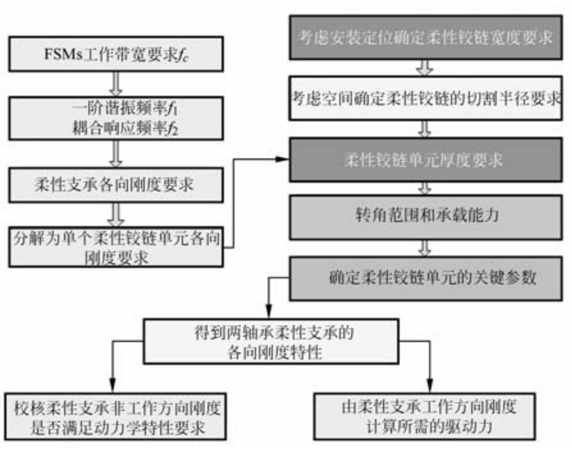

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Fig. 7 Idea and method for designing two-axis elastic support

设计实例

ز

Φ90 mm ±2 mrad

>300 Hz

. 关键尺寸参数确定

خ Hz

2～4 ⅃

2～4 ⅃

:

300 Hz

600 Hz

7

1

表 设计柔性支承的材料特性和关键尺寸

Tab. 1 Key parameters of designed new elastic support

mm	
ش R	3
t	1
b	7
D	50

	TiAl6V4
E MPa	106×10^9
ي γ	0.31
ρ kg·m^{-3}	4 450

. 设计柔性支承的各向刚度分析

MSC. patran

2

表 设计柔性支承各向刚度

Tab. 2 Stiffness of elastic support in each direction

Z	K_{θ_Z}	65 N · m rad
X	K_{θ_X}	65 N · m rad
Y	K_{γ_Y}	3.7×10^3 N · m rad
Y	K_Y	3.3×10^6 N m

Z X

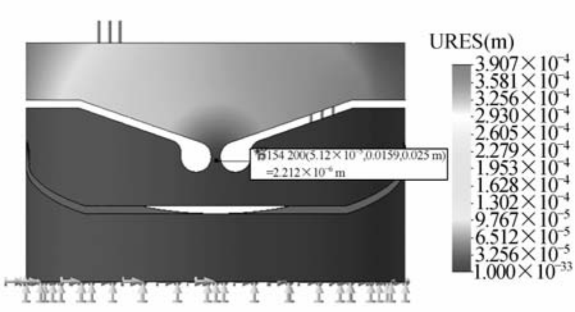
. 柔性支承回转精度分析

2

10 mrad

2. 2 μm 8 3

12



8

Fig. 8 Analysis of rotation centre offset of elastic support

. 两轴快速反射镜系统模态分析

9

9

Fig. 9 Mesh mode of motive mass in FSMs

表 快速反射镜系统各阶模态频率和模态振型

Tab. 3 Eigenvalues and mode shape descriptions of the FSMs

	Hz		
1 2	80 82	2.65×10^{-4} kg · m²	X Z
3	660	3.52×10^{-4} kg · m²	Y
4	826	0. 33 kg	Y
5	1 310	0. 33 kg	X

3 X Z 80 82 Hz Y 660 Hz

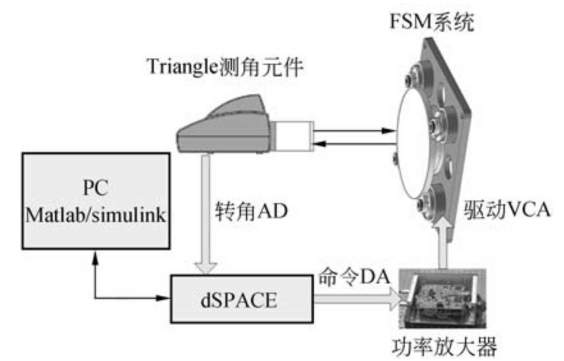
实 验

. 实验原理

10 FSM dSPACE

11 FSM 12 13 dSPACE D A FSM

BEI LA10-12-027A 4. 57mm 13. 3 N Triangle TA-HS 100-38 0. 3° 0. 15″

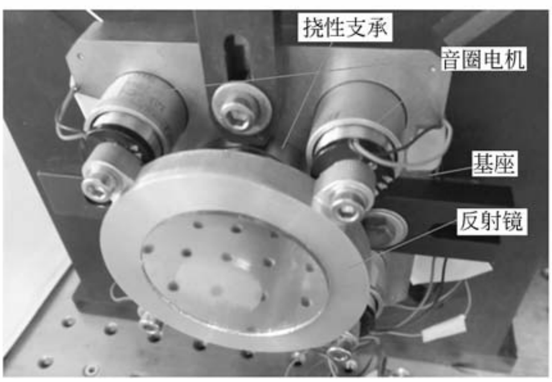


10 FSM

Fig. 10 Principle of FSM performance experiment

11

Fig. 11 Elastic support manufactured by EDM



12 FSM

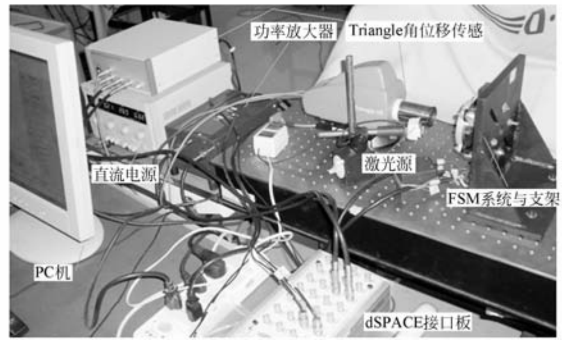
Fig. 12 Assemble of FSMs

ي 4

表 柔性支承刚度的理论设计、仿真计算和实际测试值的比较

Tab. 4 Test values theory values and simulation values of stiffness for elastic support N · m rad

X	65	65	70
Z	65	63	65

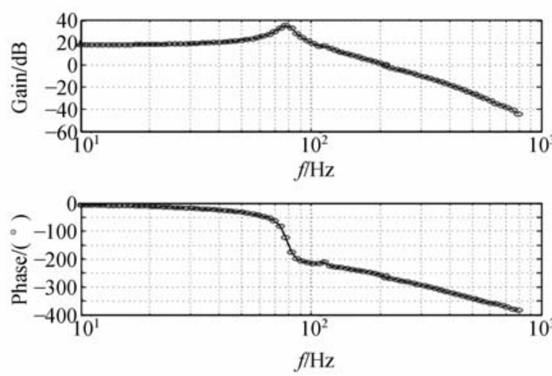


13 FSM

Fig. 13 Test platform of FSMs

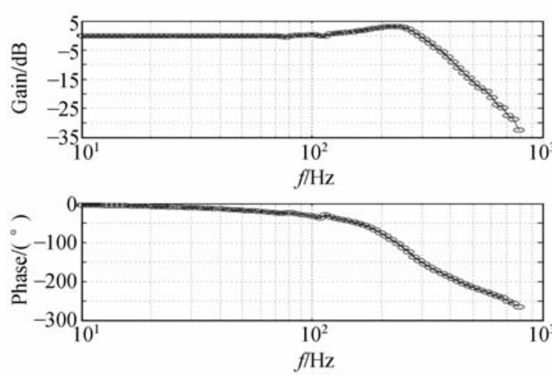
ي

10% ي



14 FSM X

Fig. 14 X-axis open-loop frequency response of FSMs



15 FSM X

Fig. 15 X-axis close-loop frequency response of FSMs

X X

Bode 14 X

77.5 Hz

80 Hz

77.5 Hz 800 Hz

PID

15 340 Hz

300 Hz

结 论

Φ90 mm ±2 mrad

>300 Hz

10%

360 Hz

>300

mrad Hz

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