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Research paper

A new bi-directional giant magnetostrictive-driven compliant tensioning stage oriented for maintenance of the surface shape precision

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ABSTRACT

Membrane mirror, known for its perspicuous feature of light weight, high packaging efficiency, low manufacturing cost and etc., has been widely used in the precision optical instruments, such as the primary mirror applied on a space telescope. However, how to maintain the membrane mirror's surface shape precision at a high level is still a challenging problem. Therefore, a bi-directional giant magnetostrictive-driven compliant tensioning stage is proposed in this research, and the basic performance of the stage is studied through theoretical analysis, numerical simulation and experimental investigations. First, the performance requirements and conceptual design are presented and illustrated in detail. Second, the Pseudo Rigid Body Model method is selected as the basis of further investigating the stage and the dynamic model is established through Lagrange's equation. Meanwhile, numerical simulations are performed to analyze the basic performances. Finally, a prototype is manufactured and based on this device, some experiments are conducted. The results indicate that the developed tensioning stage is able to achieve the desired capability and could effectively maintain the surface shape precision.

1. Introduction

Membrane mirrors, even though occurred over four decades ago with the Echo series of satellites [1], they now re-attracts scientists' attentions, especially in aerospace engineering. Typically, the aperture of an optical system should be as large as possible, in order to improve the imaging performance [2]. However, limited to the requirements of a small package volume and lightweight during the launch, it is difficult to further enlarge the aperture through traditional stiffer surface mirror technology [3]. Hence, the membrane mirror with the features of minimal mass and high packaging efficiency has been widely applied in these cases, where extremely large in-space deployable mirrors are needed [4,5]. However, a challenging question that how to realize the active surface shape control under the special outer space circumstance after successful launch is presented to researchers. After all, the higher vacuum, stronger radiation, lower gravity, extreme temperature change and micro-vibration all might severely affect the precision of the membrane mirror surface [6]. Traditionally, there are two approaches, distinguished by the location of the actuators, to achieve active surface shape control [7,8]. One is the boundary actuation, i.e., the actuators are arranged in the support ring of the mirror. The other is the in-plane actuation,

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Nomenclature

t_1	Right-circular flexure hinge thickness
t_2	Ring flexure thickness
r_1	Radius of the right-circular flexure hinge
r_2	Radius of the ring flexure
L_1	Power arm of the lever amplifier
L_2	Resistance arm of the lever amplifier
h_1	Thickness of the lever amplifier output end
h_2	Thickness of the lever amplifier fulcrum
k_{lever}	Amplifier ratio of the lever
v_c	Velocity in point *C*
v_{in}	Driving velocity
θ	Included angle of linkage *CD*
v_D	Velocity in point *D*
λ	The final amplification ratio
φ_A	Rotation angle of lever *AC*
φ_B	Rotation angle of flexure hinge *B*
φ_C	Rotation angle of flexure hinge *C*
φ_D	Rotation angle of flexure hinge *D*
φ_E	Rotation angle of flexure hinge *E*
K_A	Bending stiffness of flexure hinge *A*
K_B	Bending stiffness of flexure hinge *B*
E	Modulus of elasticity
b	Width of the flexure hinge
K_E	Bending stiffness of flexure hinge *E*
γ	Length transformation coefficient
$K_{\theta E}$	Stiffness transformation coefficient
I_E	Moment of inertia of cross section of the flexure hinge *E*
L_E	Length of the flexure hinge *E*
K_C	Bending stiffness of flexure hinge *C*
K_D	Bending stiffness of flexure hinge *D*
ρ_C	Length transformation coefficient of the ring flexure *C*
ρ_D	Length transformation coefficient of the ring flexure *D*
$K_{\theta C}$	Stiffness transformation coefficient of the ring flexure *C*
$K_{\theta D}$	Stiffness transformation coefficient of the ring flexure *D*
l_{eC}	Equivalent length of the ring flexure *C*
l_{eD}	Equivalent length of the ring flexure *D*
J_1	Moment of inertia of the lever *AC* around the hinge *A*
m_3	Mass of the slider *E*
J	Equivalent inertia moment
K	Equivalent stiffness
T'	Generalized torque applied to the system
f	First natural frequency

where active force generated by the actuator is directly applied along the normal line of the mirror surface. When further discussing the consequences of on-orbit extreme temperature change, it is obvious that a spherical temperature field, fitted by Zernike polynomials, might cause a large axial thermal deformation of the membrane mirror. This deformation influences the optical performance and can result in spherical aberrations. Aimed at this question, the boundary actuation scheme is no doubt the most effective way which has been validated by numerous studies [9–11].

However, by taking a panoramic view of the boundary actuation scheme, it is known that a large number of actuators have to be utilized to ensure a symmetric tensioning so as to obtain a high surface shape precision. Therefore a dilemma is presented to researchers, namely the more adoption of actuators, the better the effect, but the larger the added mass and more complex the control systems and appurtenances. In that case, realizing the precision control with fewer actuators becomes a very complicated technique problem. Thus, as an important pre-research, a tensioning stage based on flexure mechanism is proposed to solve this dilemma. The advantages of this scheme, compared with traditional design scheme, lie in the following: firstly, utilizing a single actuator could achieve the tensioning function which several actuators could do in previous researches; secondly, one actuator could make the tensioning of the membrane circle with better consistency,