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Analysis of a tripod flexure mechanism (TFM) for mirror sub-assemblies

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A B S T R A C T

This paper presents the analytical compliance analysis and type synthesis for a tripod flexure mechanism (TFM) which is used in the design of the mirror sub-assembly (MSA) of future inertia-confinement-fusion (ICF) facilities. To reveal the compliance characteristics of the TFM, the static compliance analysis is conducted. The analytical compliance matrix of the TFM is obtained by using the coordinate transformation method (CT-method) of compliance matrices. The parameterized compliance matrix of the TFM is derived, and it is significantly influenced by its legs' mounting angle θ. Different θ values generate different degree-of-freedom (DOF) characteristic of types. The finite element analysis (FEA) results are compared with analytical compliance elements results for different θ values. As to the linear linear-elastic deformations, the maximum compliance error of analytical model is less than 1% compared to the FE model. Enlightened by the compliance analysis of the TFM, a compliance-based type synthesis of the TFM is introduced in detailed processes, illustrating how θ affects the DOF characteristics. According to the results of the compliance analysis and type synthesis, a TFM was designed and fabricated for the MSA prototype, and it is experimentally verified. It is demonstrated that the parameterized compliance matrix provided is beneficial to design, analysis and type synthesis tasks of TFMs.

1. Introduction

Transport mirrors are key optics of the target area of ICF facilities. They are missioned to guide high power laser beams to the target [1]. To ensure the targeting accuracy, those mirrors are required to achieve a 2-D (tip/tilt) precision angular motion. Mirror sub-assemblies (MSAs) are designed for mounting transport mirrors and providing them required motions for the mirrors. A key task in design of MSAs is to kinematically support those mirrors and offer them required DOFs. Flexures have been widely used in the field of opto-mechanical design for: (1) elastic optical mountings to maintain high optical performances under operational levels of shock, vibration, pressure, and temperature variations [2–5]; (2) kinematic mechanisms to provide high precision and repeatable motions that are free of mechanical friction, backlash, wear [6,7]. In a traditional MSA, a group of kinematic couplings was used to constrain the transport mirror and provide the required motion. There were inevitable friction and contact stress concentrations between contacting surfaces. Those concentrations may cause significant distortion, leading to considerable parameter changes of clearance and friction, which may decrease the precision and repeatability of motion of the MSA. In this paper, a TFM is used as the ball-joint in MSA. Compared to kinematical couplings and other multi-leg mechanisms, the TFM has many advantages, including (1) the capability of providing pure rational DOFs; (2) high translational stiffness and load capacity; (3) light weight with simple structure; (4) free of joint friction; (5) ease of fabrication, cleaning and supporting-actuation configuration; (6) the capability of large range and high repeatability of motion.

A typical TFM consists of a moveable platform, a base and three axially configured flexure legs or chains (often identical). The platform is supported by the elasto-kinematic legs with various typologies, such as single flexures (i.e., beams, rods, blades or notched-hinges), multiple flexures (serial, parallel or hybrid). Integrated with actuators, the platform can offer various motion behaviors. TFMs are planar or spatial flexure parallel mechanisms (FPM) for different leg configurations. A TFM with coplanar legs is a planar parallel mechanism [8–12]. In more complicated designs, TFMs are spatial parallel mechanisms for the legs have an identical mounting angle with the central axis [13–16]. The major difference of those TFMs is the different typologies of the flexure legs they employed (i.e., leaf-spring legs [13], wire legs [14,16], and spatial hybrid legs [15]). The design intention of TFMs was aimed at achieving desired motion behaviors. Parallel mechanisms clearly have the advantages over the serial mechanisms for high stiffness, compactness, and small positional errors [17].

Compliance (or stiffness) is one of the most important performances of a flexure mechanism [18]. Therefore, it is quite necessary to perform the compliance modeling and evaluate the compliance property of a

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flexure mechanism in the early design stage. A negative feature of FPMs is the complexity of analysis, especially for spatial FPMs. Much work has been done to study the compliance analysis of FPMs. So far, two different approaches are used to analyze the compliance of a FPM: FEA and analytical modeling [19]. FEA is effective and efficient, however, it does not reflect the analytical compliance relationship between flexure elements in a FPM. Moreover, the accuracy of this method is highly depend on the number and quality of elements. Analytical methods can establish analytical compliance relationships of flexure elements along working directions (reduced analytical modeling [19]) or all directions (full analytical analysis). Generally, compliance behavior of a flexure is characterized by a stiffness or compliance matrix in Cartesian space [20]. Based on coordinate transformation of those matrices, the CT-method [21–23] has been developed to analyze flexure mechanisms, especially for FPMs. This method reports the compliance and stiffness matrices for flexure mechanisms, and is more flexible than FEA especially in early phase of the design cycle [21]. The CT-method has been widely used for compliance analysis [13,16,24].

Although the structure of the TFM in this paper has been proposed in Hopkins' works [25,26], its compliance and DOF properties have not been studied yet which are important for design works. Thus, a detailed and in-depth study on above issues is needed. In particular, how the mounting angle θ of the leg will affects the compliance and DOF characteristics of the TFM. To investigate this issue, in this paper, the compliance analysis and type synthesis of the TFM is considered simultaneously. First, we derived the parameterized compliance matrix of the TFM, which is expressed as functions of θ. By using the matrix, the compliance property of the TFM affected by θ is studied, and a compliance-based type synthesis work of the TFM is presented in detail.

The rest of paper is organized as follows: Section 2 demonstrates the working principle of a TFM in MSA; Section 3 presents the compliance derivation and analysis work; Section 4 shows the compliance validation work by using FEA; Section 5 introduces the type synthesis work; Section 6 shows the fabrication and testing work of the TFM for MSA design; Section 7 draws conclusions and introduces future works.

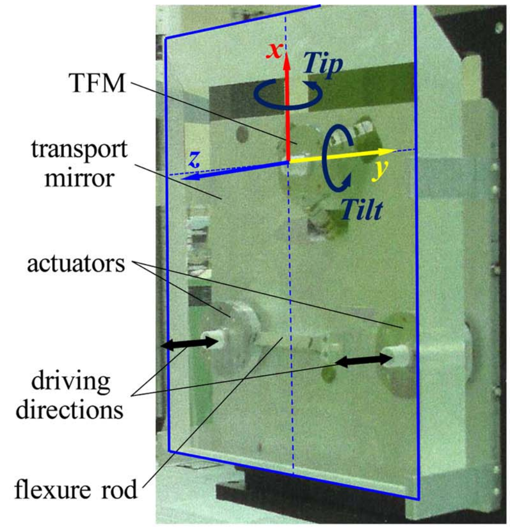
2. Background

As shown in Fig. 1(a), the transport mirror in the MSA is required to achieve 2-DOF pure rotations (tip and tilt) with μrad-class precision [1]. Thus, the flexure mechanism selected for the MSA must possess at least two rotational DOFs without translational DOFs. Besides, the flexure mechanism could be placed at the back of the mirror for compact and modular system design. For above design objects, the TFM having three independent rotational DOFs, is used to support the mirror and provide required DOFs. As shown in Fig. 1(b), the TFM with three axially configured flexure legs is a FPM. With four equally spaced blades in series, each leg provides five DOFs and one axial constraint that is kinematically equivalent to a wire flexure. Thus, the TFM is functionally act as a spherical pivot [25,26] with a redundant in-planar rotational DOF for MSA. To avoid such rotation, a flexure rod is added to constrain the redundant DOF. Then, by using two actuators, the mirror could be tipped or tilted as desired.

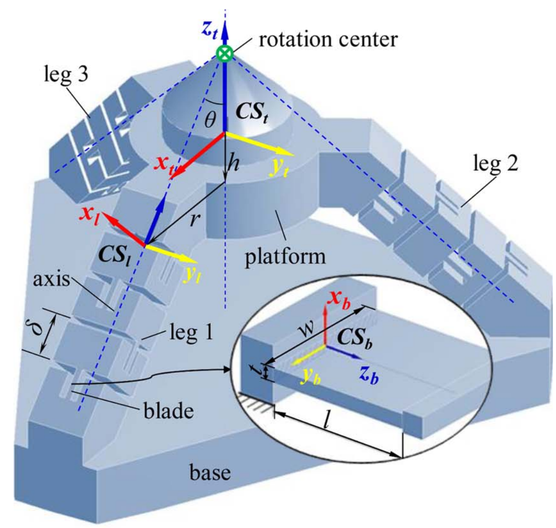
The TFM, shown in Fig. 1(b), will present different compliance and DOF properties with variable $\theta \in [0°, 90°]$. However, little effort has yet been devoted to explore the 'θ-compliance-DOF' characteristics of the TFM. Therefore, as an objective of this paper, the 'θ-compliance-DOF' properties are figured out in details to guide the mechanical design of the TFM into MSA application in following sections.

3. Compliance analysis

This section is mainly about the compliance analyses of the TFM. Its compliance matrix is derived as a function of θ. Taking advantage of this matrix, we can characterize the compliance and DOF properties of the TFM affected by θ. Note that, the analyses in this section focus on



(a)



(b)

Fig. 1. MSA with a TFM: (a) MSA, (b) geometry of the TFM.

small elastic motions with the dynamic while the nonlinear behaviors associated with inertia are ignored.

3.1. Analyzing method and steps

The CT-method is a general and completely parametric approach for analyzing flexure mechanisms [21]. Once the 6 × 6 compliance matrix $\boldsymbol{C}$ or the stiffness matrix $\boldsymbol{K}$ of a flexure mechanism is formed in one coordinate system CS, by using a 6 × 6 transformation matrix $\boldsymbol{T}$, it can be reflected to any another coordinate system CS' as $\boldsymbol{C}'$ or $\boldsymbol{K}'$. Then, the compliance or stiffness relationship before and after transformation is

$$\begin{cases} \boldsymbol{C}' = \boldsymbol{T}^{-T}\boldsymbol{C}\boldsymbol{T}^{-1} \\ \boldsymbol{K}' = \boldsymbol{T}\boldsymbol{K}\boldsymbol{T}^{T} \end{cases} \tag{1}$$

where the superscript "T" represents the matrix transpose. The matrix $\boldsymbol{T}$ can be calculated as

$$\boldsymbol{T} = T(\mathbf{V}) = \begin{bmatrix} \boldsymbol{R} & \boldsymbol{0} \\ \boldsymbol{DR} & \boldsymbol{R} \end{bmatrix} \tag{2}$$