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Design of planar static balancer with associated linkage

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ABSTRACT

This paper presents a design method for a static balancer with associated linkage. Various mechanisms can be obtained with modifications to the associated linkage. Gravity compensators for various mechanisms can be achieved similarly from a gravity compensator for the associated linkage. The space mapping method is adopted to design a gravity compensator for the associated linkage. Conversion rules are derived by investigating the variances of a mechanism from the associated linkage and are applied to the design equation for the associated linkage generated by the space mapping method. Rows and columns of the design equation are deleted by conversion rules, leading to deletion rules. A new gravity compensator for the mechanism derived from the associated linkage is obtained by applying the deletion rules to the design equation (i.e., gravity compensator) for the associated linkage. The four-bar mechanism is adopted as the associated linkage, and various gravity compensators for planar mechanisms are derived from the gravity compensator of the four-bar linkage. Simulations are conducted, and the results show that complete gravity compensation is possible for various planar mechanisms.

1. Introduction

Gravity compensators with springs have been proposed for several decades. Nathan has proposed a 1-DOF (degree of freedom) gravity compensator in which one end of a spring is fixed at the base and the other end is attached at a moving link [1]. Ulrich and Kumar have suggested a 1-DOF gravity compensator that uses wire and a pulley [2]. An internal cam mechanism has been designed by Koser and applied to a five-bar mechanism [3]. Herder has presented a static balancer for a variable load equipped with a storage spring [4]. A hybrid design has been suggested in which a parallel linkage is adopted to indicate the COM (center of mass) [5]. A 2-DOF gravity compensator for roll-pitch rotations has been proposed [6]. The roll-pitch rotations are decoupled with bevel gears, and two 1-DOF gravity compensators are installed at the rotating bevel gears. Static balancers of a parallel mechanism have been studied using counter masses and springs [7,8]. A gravity compensator for a service robot has been developed [9]. A gravity compensator using a hemispherical magnet has been proposed [10]. Relations between static balancing parameters of the cognates of a four-bar linkage have been studied and a static balancing method for a general n-DOF revolute and spherical jointed rigid-body linkages has been developed [11].

This paper proposes a design method of a static balancer by which gravity compensators of various mechanisms are obtained from a gravity compensator of the associated linkage. Gravity compensators of various mechanisms are designed with intensive analyses of various mechanisms (e.g., computation of the potential energy) in general. In the proposed method, however, gravity compensators of various mechanisms are simply obtained with modifications to the gravity compensator for the associated linkage.

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Various mechanisms can be obtained with modifications to the associated linkage. For example, the slider crank is derived from the four-bar linkage by replacing a revolute joint with a prismatic joint. When the associated linkage is converted into a new mechanism, some joints are ignored, and some masses of linkages are merged into adjacent links. Therefore, conversion rules are derived by investigating the variances of the mechanism derived from the associated linkage.

The space mapping method [12] is adopted to design a gravity compensator for associated linkage. The mapping between joints and unit gravity compensators is determined with the mapping matrix, and the design equation is derived. The mapping matrix indicates both the number of unit gravity compensators and their locations (i.e., their kinematic constraints). The conversion rules are applied to the design equation for the associated linkage generated by the space mapping method. Rows and columns of the design equation are deleted by using the conversion rules, resulting in a new design equation and a new mapping matrix for the derived mechanism. The so-called deletion rules are obtained. Hence, gravity compensators for mechanisms derived from the associate linkage can be simply obtained from the gravity compensator for the associate linkage by applying the deletion rules. In this paper, the four-bar mechanism is adopted as the associated linkage, and various gravity compensators for planar mechanisms are derived from the gravity compensator of the four-bar linkage. Simulations are conducted, and the results show that complete gravity compensation is possible for various planar mechanisms.

2. The space mapping method

The design of a spring balancer is considered as a mapping between two spaces (i.e., the joint space for gravitational torques and the gravity compensator space for compensating torques). The mapping matrix indicates the mechanical connections of unit gravity compensators with respect to a target mechanism. The design method with space mapping is briefly summarized in this paper. Please refer to [12] for more details.

2.1. Space mapping

The joint space is predetermined as $\boldsymbol{\theta} = [\theta_1, \theta_2, \ldots, \theta_n]^T \in R^{n \times 1}$, where θ_i denotes the rotation angle of the i-th joint, and n represents the number of joints. For simple analysis, we assume that the gravity compensator space consists of only a 1-DOF gravity compensator. In this case, the gravity compensator space can be determined as $\boldsymbol{\theta}_g = [\theta_{g1}, \theta_{g2}, \ldots, \theta_{gm}]^T \in R^{m \times 1}$, where θ_{gi} denotes the rotation angle of the i-th gravity compensator, and m represents the number of 1-DOF gravity compensators.

The rotation angles of the gravity compensators (i.e., $\boldsymbol{\theta}_g$) are passively determined by the pose of the mechanism (i.e., $\boldsymbol{\theta}$). Thus, functions or relationships exist between the joint space and the gravity compensator space. Suppose that $\boldsymbol{\theta}_g$ is computed with $\boldsymbol{\theta}$ as follows:

$$\boldsymbol{\theta}_g = \mathbf{J}\boldsymbol{\theta} + \boldsymbol{\phi} \tag{1}$$

where $\mathbf{J} \in R^{m \times n}$ and $\boldsymbol{\phi} \in R^{m \times 1}$. $\mathbf{J}$ denotes a mapping matrix between the joint space $\boldsymbol{\theta}$ and the gravity compensator space $\boldsymbol{\theta}_g$, and $\boldsymbol{\phi}$ represents a vector of constant phase angles.

2.2. Potential energy in both spaces

Let ${}^0\mathbf{P}_i$ be the position of the COM of link i with respect to the {0} frame. Then, the potential energy of mass m_i is obtained by

$$V_m = -\sum_{i=1}^{n} m_i \mathbf{g} \cdot {}^0\mathbf{P}_i \tag{2}$$

where $\mathbf{g}$ represents the gravitational vector. ${}^0\mathbf{P}_i$ is computed from $[{}^0\mathbf{P}_i;1] = {}^0\mathbf{T}_i[{}^i\mathbf{P}_i;1]$, where ${}^0\mathbf{T}_i = {}^0\mathbf{T}_1 {}^1\mathbf{T}_2 \ldots {}^{i-1}\mathbf{T}_i$ denotes the transformation matrix. Because ${}^0\mathbf{T}_i$ is determined by $\boldsymbol{\theta}$, Eq. (2) represents the potential energy in the joint space.

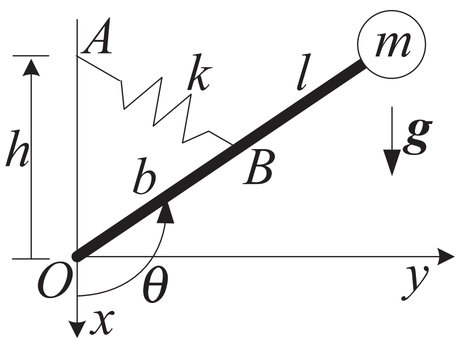

Fig. 1. A 1-DOF gravity compensator [1].