Mechanism and Machine Theory 130 (2018) 301–312

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmachtheory

Research paper

Design of one DOF closed-loop statically balanced planar linkage with link-collinear spring arrangement

Chi-Shiun Jhuang, Young-Yu Kao, Dar-Zen Chen*

Department of Mechanical Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan

ARTICLE INFO

Article history:
Received 28 December 2017
Revised 15 May 2018
Accepted 30 July 2018

Keyword:
Closed-loop
Balanced
Spring
Link-collinear

ABSTRACT

Several methods have been proposed for reducing the space required for a spanning-spring arrangement in a statically balanced mechanism (SBM) with auxiliary elements. This paper proposed a designing method to overcome the problem traditionally caused by the interference of the spanning-spring arrangement and the use of auxiliary elements. A prismatic joint is required for designing the proposed one DOF, closed-loop, planar linkage with a link-collinear spring arrangement. In our design, two prismatic joints are required for a closed-loop, planar four-link SBM to achieve static balance by deriving the formulation of elastic energy. Moreover, these two prismatic joints should be adjacent and perpendicular to each other. Furthermore, at least one of the prismatic joint must be adjacent to the ground link. On the basis of the design principles of the four-link SBM, a six-link SBM with two independent loops is also discussed. The ground link must be the link connected to the common joints and with the maximum number of ground-adjacent links. And one prismatic joint must be set as the common joint for reducing the number of the prismatic joints from four to three.

1. Introduction

A statically balanced mechanism (SBM) is a well-known mechanism for achieving the sum of the gravitational energy and elastic energy is constant. This mechanism is used to keep the position of payload, such as angle-poise lamp and surgical light, in its workspace by eliminating the influence of gravity [1–3]. The influence of gravity can be eliminated using an SBM, which can improve the efficiency of actuators through system control [4,5]. In addition, SBMs can be used in several applications (such as training or assistance devices) to resist or assist the movement of limbs by acting as a resistance force or resist gravity [6–9].

Static balance is typically achieved through friction, counterweight, and spring methods. However, the counterweight method increases mass and inertia in the system. The friction method would fail because of friction decays due to joint worn out. The spring method is based on the methodology of conservation of potential energy, in which static balance is achieved when the total gravitational energy and elastic energy of the system are perfectly balanced [10–13]. Consequently, the system has a smaller inertia than which is balanced by counterweight method.

Most design principles proposed in the literature focused on the open-loop mechanism along with the spanning-spring arrangement to overcome the influence of gravity. In the open-loop mechanism, the degree of freedom (DOF) can be increased easily; for example, the DOF of a mechanism increases by one when a link is added in the open-loop linkage [14].

* Corresponding author.
E-mail address: dzchen@ntu.edu.tw (D.-Z. Chen).

https://doi.org/10.1016/j.mechmachtheory.2018.07.021
0094-114X/

The spanning-spring arrangement is characterized by the connectivity of the spanning structure among the links. Hence, this arrangement is convenient for achieving static balance by installing the spring between two arbitrary links. Lin et al. [15] proposed an admissible spring configuration matrix and reported the admissible configurations of the spanning-spring arrangement of open-loop mechanism for static balance.

However, the SBM has some limitations in practical applications: (1) the rigidity of SBM for open-loop structures is lower than that for closed-loop structures; (2) an SBM with a spanning-spring arrangement requires more space; (3) the spanning spring may interfere with other moving links during the movement of the linkage.

To overcome the aforementioned problems, some studies have proposed SBMs wherein the space required by the spanning spring is reduced using auxiliary elements to rearrange the spring configuration. Most of them have used cables and appropriate cam profiles to reconfigure the spanning springs [16–18]. Nakayama et al. [19] used cables and cams to investigate an SBM implemented in a gear system. The system comprised gears attached to a joint shaft with pulleys and crossing wires. Cho et al. [20] proposed a methodology for designing a bevel gravity compensator with a zero-free-length (ZFL) spring. In an auxiliary gear system with a joint, the spanning spring can be installed within the links; and the spanning spring works with the moving link. However, the use of auxiliary elements has some drawbacks. For example, (1) auxiliary elements impose additional loadings on the system; (2) motion interferences between the auxiliary elements and links may affect the workspace of the SBM; (3) the use of cables may result in a complicated spring configuration, and the cables have low reliability for long-term use.

Therefore, in this paper, a novel and promising SBM using compression springs is proposed the influence of gravity. The compression springs are parallel and coaxial with the moving link; thus, using the compression springs to achieve static balance avoids the aforementioned problems associated with the spanning-spring arrangement. Kim and Song investigated a two-link module with a compression spring for overcoming the influence of gravity [21]. The spring was compressed by a block pulled by the cable. Van Dorsser et al. [22] proposed a gravity equilibrator for adjusting the stiffness of the compression spring; here, a cable was attached to an inverted pendulum and placed on a pulley. Koser [23] reported a cam-type SBM with a compression spring in which the elastic energy is stored based on the designed cam profile. Takesue et al. [24] proposed a compensation mechanism for different gravities by using two 90°-phase-difference compression springs with a rotation follower. However, these studies have focused on the open-loop mechanism and the use of auxiliary elements in the design, and still suffer from the aforementioned problems associated with the open-loop mechanism and auxiliary elements.

In this paper, the method for designing a closed-loop SBM with a link-collinear spring and without auxiliary elements is proposed to enhance the rigidity of SBM and to avoid the use of auxiliary elements. By using the link-collinear spring arrangement, the problems of interference and lack of reliability of cables can be overcome. The remainder of this paper is organized as follows. Section 2 introduces the static balance of the SBM. The link vectors and joints in the system are defined, and the formulation of gravitational energy and elastic energy by using prismatic joint vectors is presented. Hence, the equation of total potential energy for the linkage is obtained. In Section 3, the determination of the link-collinear spring arrangement for the four-link SBM is derived according to the total potential energy equation. The admissible four-link SBM with link-collinear spring arrangement are obtained. In Section 4, on the basis of the design principles of the four-link SBM, the arrangement of link-collinear spring for a six-link SBM with two independent loops is determined. For the six-link linkage, the location of the ground link is determined using additional design rules, and the number of springs can be reduced by setting the prismatic joint as the common joint. In Section 5, the illustrative examples for the four- and six-link SBMs are presented, and the simulated results are presented to verify the design concept.

2. Potential energy of SBM with link-collinear springs

2.1. Position vector of mass center of revolute joint and prismatic joint

The gravitational energy of the system can be expressed as the scalar product of the vector of gravitational acceleration, the mass and position vector of the mass center, and applied to each of the system's rigid bodies. The coordinate system can be defined using complex number notations for vectors, the complicated algebraic operations of trigonometric functions can be avoided, and the derivations for both gravitational and elastic energy of the system can be simplified. Consider an arbitrary linkage for a planar n-link linkage as shown in Fig. 1; link u connecting the revolute joints or prismatic joint and the link vector $\boldsymbol{r_u}$ can be represented as

$$\boldsymbol{r_u} = |\boldsymbol{r_u}|e^{i\theta_u} \tag{1}$$

where $|\boldsymbol{r_u}|$ denotes the magnitude of $\boldsymbol{r_u}$ and is equal to the length of link u, and θ_u represents the orientation of vector $\boldsymbol{r_u}$ measured with respect to the negative imaginary axis. All orientations measured in this paper are counterclockwise.

Note that $\boldsymbol{r_u}$ is the link vector measured from the proximal joint or proximal end of the link to distal joint, where J_{u-1} is the proximal end of the link $u-1$; J_u is the proximal revolute joint of link u or prismatic joint of link u; and J_{u+1} is the distal revolute joint of link u. Hereinafter, all vectors are represented in boldface characters.

Let us assume that the mass of the link is uniformly distributed; the mass center m_u is located at the geometric center of the link u. The coefficient of position vector of mass center p_u is $\frac{1}{2}$ and 1 for revolute joint and prismatic joint, respectively.