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Static balancing of an inverted pendulum with prestressed torsion bars

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a method for the design of a statically balanced inverted pendulum. The non-linear moment-rotation characteristic of the pendulum's weight is approximated by a piecewise linear characteristic. Each transition is realized by engaging or disengaging one or more torsion bars, by means of mechanical stops. The whole set of torsion bars is located along the hinge axis of the pendulum. A prototype with three parallel torsion bars was built. Experimental evaluation of the prototype revealed a 99% work reduction of the balanced pendulum with respect to the unbalanced one.

1. Introduction

In order to alleviate the operating forces of mechanical devices, it is possible to apply static balancing to counteract the weight of the system and/or its payload [1]. The result is a more manageable device in the case that it is human-operated, and less powerful actuators in the case that the device is powered. Other advantages of static balancing include intrinsic safety [2], intuitive man-machine interaction [3,4], backlash reduction due to presstress, and weight reduction of motors and brakes [5]. Because of these advantages static balancing of weight has been proposed in numerous applications, especially in the fields of robotics [6–10], orthotics and assistive devices [11–13], and consumer products [14].

Most static balancing techniques involve the use of counter-masses [15], which have the disadvantage of increasing the overall mass and inertia of the system. A common alternative is to use extension springs [1], which have the disadvantage that the volume they occupy increases when the spring is loaded. In addition, most spring-based balancing techniques rely on the use of a special type of spring, namely a zero-free-length spring (ZFLS), which is not a common off-the-shelf component. Some authors have presented ways to circumvent the need for ZFLS proposing alternative balancing methods that are based on conventional springs with non-zero free-length [16–19,11].

Both kind of extension springs often have the disadvantage that the volume they occupy crosses the empty space between the elements of the device, which implies that the space is not available for other purposes. Think for example of an application where static balancing is to be applied in a foldable structure, such as a foldable sea container [20], to compensate the weight of the members of the structure. If there were extension springs crossing the free space inside the structure, this space would not be available for goods. Therefore more compact solutions that solely occupy space near the hinges are sought.

Koser [21] present a cam mechanism in combination with a compression spring that is designed as a compact unit at the base of

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a robotic manipulator. However, the assessment of the practical applicability of the concept is not completed up to the level of component design and physical evaluation. In practice, the high forces on the cam system combined with the very small design space may reveal as the limiting factors.

Shieh [22] presents a balancing mechanism that does not cross the free space by applying a Scotch Yoke spring mechanism which can be integrated within the link. Friction in the sliding parts are probably affecting the performance of balancing significantly, but the authors make no mention of this possible issue.

The employment of torsion springs at the hinges of a linkage would eliminate the named disadvantages. Torsion springs, namely, act at the point of rotation between two bodies and thus do not elongate when loaded. Very little work has been found that includes torsion springs for the purpose of balancing weights.

Gopalswamy [5] balances the weight of a parallelogram linkage with a single torsion spring with a linear characteristic. The range where the balance applies, however, is limited to the part of the sine characteristic that can be approximated as linear.

Trease [23] developed a gravity balanced four-bar linkage. An optimization procedure was used to obtain a constant potential energy of the masses and the open-cross compliant joints, a type of torsional springs. As the authors state, the presented solution is a specific one limited to the given parameter set only. A similar result was obtained by Radaelli [24], who developed a general design method for approximate static balancing of linkages with torsion springs. In one of the examples, a pendulum is balanced by an additional double link, obtaining in fact a four bar linkage with a balanced weight. In both cases the links that are added to balance the pendulum occupy a considerable amount of space. Therefore, in this regard, these solutions do not offer enough advantage with respect to the helical spring balancers.

In the present paper the case is considered of a body, modelled by a point mass connected by a weightless link to a revolute joint in an inverted pendulum arrangement, representing, e.g., a side wall of a foldable sea container. The pendulum moves over ninety degrees from the upright vertical position to a horizontal position. The weight will be balanced with torsion springs, namely torsion bars. Torsion bars have the advantage that they occupy approximately the same space loaded as unloaded. Moreover, normally the bars are situated at the hinge in the direction perpendicular to the plane of motion of the pendulum. This is especially advantageous for pendulums with large out-of-plane width, such as the side wall of the container.

Since normal torsion springs have a linear moment-angle characteristic, they can only linearly approximate the sinusoidal moment-angle characteristic of the weight. We propose the judicial employment of mechanical stops and prestress for the sequential activation or deactivation of different torsion bars in order to result in a piecewise linear moment characteristic. This piecewise linear characteristic can give better approximations of the nonlinear degressive characteristic of the weight.

Eshelman [25] describes an invention where a multi-rate torsion bar is employed for vehicle suspensions. An increased torsional stiffness is obtained with two serial torsion bars with one mechanical stop. Also Fader [26] describes a similar torsion bar for vehicle suspensions, where more mechanical stops are used to affect the total torsion stiffness of the bar. In his invention, Castrilli [27] obtains non-linearity in the torsion characteristic of a bar with a continuous contact profile along the length of the bar. This system can be regarded as an infinite number of bars of infinitesimal length in series, all with their own contact point.

All mentioned inventions concern torsion bars with increasing stiffness. A degressive stiffness, however, can only be obtained if the stops make contact initially, i.e. one or more bars are prestressed. Claus [28] designed such a system for static balancing of the walls of a foldable container. In a small-scale prototype he used a configuration of two serial torsion bars with one mechanical stop. No other examples of torsion spring systems with positive but degressive stiffness were found by the authors in literature.

The goal of this paper is to propose a method for balancing an inverted pendulum by a piecewise linear approximation of the nonlinear characteristic, obtained by the sequential (de-)activation of torsion springs. The design approach allows for unlimited number of linear segments. This number is only limited by the physical implementation of the torsion bars.

The outline of this paper is as follows. In Section 2 the design methodology is described. Section 3 illustrates the design of the physical prototype, while in Section 4 the testing procedure and the test results are provided. Finally a discussion and some conclusions can be found in Sections 5 and 6, respectively.

2. Method

The present section starts with a description of the technical problem and of the conceptual solution. After that the design method will be discussed.

2.1. Problem description

Consider the system depicted in Fig. 1a. A point mass m is attached to a weightless rigid link at a distance l from a hinge. The pendulum is allowed to move between its upright vertical position a, and 90° clockwise, to the horizontal position b, thus $[a, b] = [0, \frac{\pi}{2}]$ rad. The weight of the pendulum produces a negative sinusoidal moment-angle characteristic at the hinge. Friction and other non-conservative forces are neglected. To maintain the system in equilibrium at every position, a system with a positive sinusoidal moment characteristic is needed to counteract the weight, see Fig. 1b. Focusing on the given range of motion it is required that the balancing system possesses a non-linear, positive and decreasing stiffness.

A given design requirement is that the balancing system occupies as little space as possible around the hinge. In a sea container, the direction out of the plane of motion is along the hinge of the wall, thus along this hinge there is space available for the balancing system. This requirement practically excludes the employment of extension springs.

The high non-linearity and particularly the decreasing stiffness property makes it hard to think of solutions with normally