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Design and analysis of closed-chain principal vector linkages for dynamic balance with a new method for mass equivalent modeling

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ABSTRACT

For high-speed robotics dynamic (shaking) force and (shaking) moment balance are important properties to obtain low base vibrations, high precision, and short cycle times, a.o., while for large moving structures such as movable bridges and movable roofs force balance is important for safety and low energy usage. To find applicable solutions, dynamic balance can be considered in the very beginning of the design process by synthesis from principal vector linkages: fundamental kinematic architectures with inherent force balance.

Succeeding the already studied open-chain principal vector linkages, this paper introduces the design and analysis of closed-chain principal vector linkages with two approaches. With the proposed open-chain method solutions are obtained by simply closing the chain of an open-chain principal vector linkage. With the proposed method of the mass equivalent principal chain less complex solutions are obtained with consideration of the loop closure relations. Then an open-chain principal vector linkage is closed with an additional element which, with a general mass distribution, is modeled mass equivalently in a new way with two real equivalent masses and one virtual equivalent mass. The results are validated with a dynamic simulation and a grasper mechanism with payload balanced together is shown as application example.

1. Introduction

The design of multi degree-of-freedom (DoF) mechanisms or manipulators that are dynamically balanced (i.e. shaking-force balanced and shaking-moment balanced) is increasingly important for high-speed applications such as pick and place tasks in the production and packaging industries. With dynamic balance base vibrations are eliminated which leads to, among others, improved accuracy and reduced cycle times [1,2]. For large moving structures such as movable bridges and movable roofs force balance is important for low energy usage and safety [3].

For a mechanism to be force balanced it is required that the linear momentum of all moving elements together is constant for any motion and for moment balance of a mechanism it is required that the angular momentum of all moving elements together is constant for any motion. As a consequence, the center of mass (CoM) of a force balanced mechanism is in a stationary point in the base for any motion [4]. This means that gravity has no effect on the motion of the mechanism and on its performance, a property also known as static balance. Therefore force balanced mechanisms are statically balanced too.

A considerable challenge in the design of balanced mechanisms is to obtain solutions that are applicable and profitable in practice. Generally dynamic balance solutions lead to a significant, if not enormous, increase of mass, inertia, and complexity which prevents them from being applied without deteriorating the overall performance [4,3]. Instead of aiming at balancing a mechanism

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after its kinematic synthesis with techniques as shown in [5–7] it therefore is important to consider dynamic balance already in the very beginning of the design process. Up to date this can be best achieved by synthesis of balanced mechanisms from so called *principal vector linkages*, which are fundamental kinematic architectures with inherent force balance [8,9] from which also moment balance solutions can be derived [10]. With this approach already various promising results have been obtained such as a high-speed dynamically balanced parallel manipulator [2], a 2-DoF dynamically balanced grasper [9], and new designs of movable bridges and movable architecture [3,11].

The goal of this paper is to propose methodology for the design of *closed-chain* principal vector linkages. Different from the principal vector linkages in [9,10], which are open-chain principal vector linkages consisting of an open chain of principal elements, it is shown in this paper how principal vector linkages consisting of closed chains of principal elements can be designed. From these linkages it is possible to synthesize new types of inherently balanced mechanism solutions.

Two approaches for the design of closed-chain principal vector linkages will be introduced and investigated. In Section 2 it is shown how with the proposed *open-chain method* closed-chain principal vector linkages are derived by closing the chain of principal elements of an open-chain principal vector linkage. This is a straightforward method which is easy to apply. However the resulting solutions are more complex than required since the loop closure relations are not considered.

For the design of closed-chain principal vector linkages with consideration of the loop closure relations, it is proposed to close an open-chain principal vector linkage with an addition element and to model this additional element mass equivalently for including it in the calculations. First in Section 3 it is derived how an element with a general mass distribution can be modeled mass equivalently in a new way with real and virtual equivalent masses. For elements with a CoM along the line through the two joints it is well known that it can be modeled mass equivalently with two equivalent masses, one in each joint, when their sum equals the mass of the element and their combined CoM is at the same location as the element CoM [12,13]. How to model an element with a general CoM that is not along the line through the two joints however is new.

Subsequently it is shown in Section 4 how with this new mass equivalent model a closed-chain principal vector linkage can be designed. The equivalent masses are projected on the open-chain principal vector linkage which then becomes a *mass equivalent principal chain* (MEPC). Then from the MEPC the design parameters are calculated.

In Section 5 the results are validated with a dynamic simulation and by deriving the known force balance conditions of a general 4R four-bar linkage. In Section 6 it is shown that the method of the mass equivalent principal chain is general and can be applied for the design of closed-chain principal vector linkages with any number of principal element connected in series or in parallel, with multiple closed loops, and with closed chains with inner elements.

2. Open-chain method

In this section it is shown how with the proposed *open-chain method* closed-chain principal vector linkages are derived by closing the chain of principal elements of an open-chain principal vector linkage without considering the loop closure relations.

Fig. 1 shows one of the various open-chain principal vector linkages: the 4-DoF principal vector linkage from [9,3]. It consists of four principal elements that are connected in series with pivots in the principal joints A_1, A_2, and A_3 and the twelve principal vector links P_1B_1, P_2B_1, P_2B_2, P_3B_2, P_3B_3, P_4B_3, B_1C_1, B_2C_1, B_2C_2, B_3C_2, C_1S, and C_2S that are arranged as parallelograms with pivots in the principal points P_1, P_2, P_3, P_4 of each principal element. The principal dimensions a_1, a_{21}, a_{23}, a_{32}, a_{34}, and a_4 determine the locations of the principal points and also the lengths of the principal vector links. Each of the sixteen elements has a generally located CoM and the CoM of the complete linkage is in joint S for any motion. This means that the linkage is force balanced about joint S and

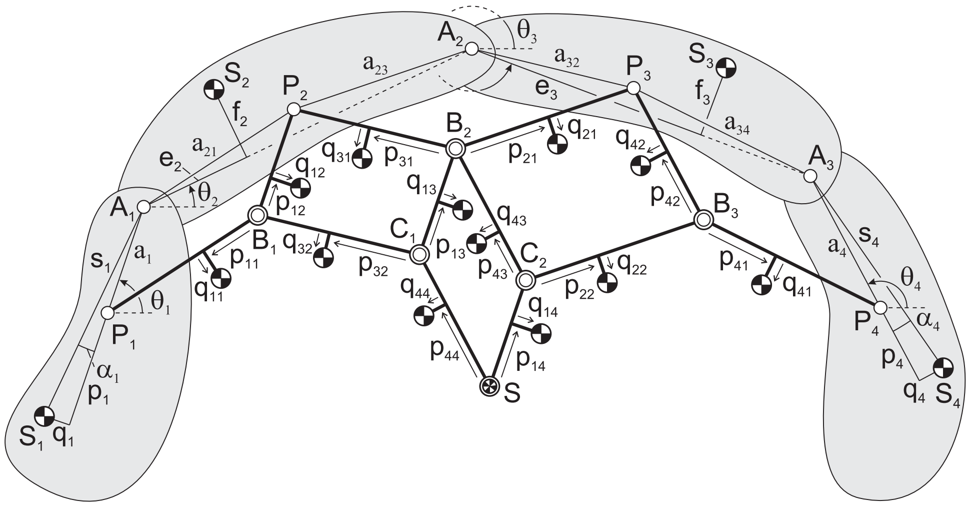

Fig. 1. Open-chain principal vector linkage of four principal elements in series with pivots in A_1, A_2, and A_3 and twelve principal vector links. All elements have a general CoM and the common CoM of all elements is in joint S for any motion.