MODAL AND KINETO-ELASTODYNAMIC ANALYSES OF BALANCED FOUR-BAR LINKAGES

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Abstract. This paper investigates the effects produced by two common techniques of force and static balancing on the dynamic performances of closed-chain linkages, taking into account the flexibility of the mechanism components. The long-term goal of the research consists in determining an optimal balancing strategy for parallel spatial manipulators. The present contribution is a starting point and it focuses on the planar four-bar linkage, intended as the simplest example of closed-chain mechanism. The dynamic performances of an unbalanced four-bar linkage and two balanced ones, respectively obtained by mass and elastic balancing, are numerically compared. The natural frequencies and mode shapes of these mechanisms are estimated by modal analysis, whereas the dynamic performances at three different operating regimes are assessed by kineto-elastodynamic investigation. The purpose of this study is to obtain preliminary results, to be refined and broadened in future developments.
1 INTRODUCTION

A mechanism is said to be *statically balanced* (or *gravity compensated*) if no driving actions are required to withstand gravity loads, regardless of the mechanism configuration. In such an instance, the actuators impart accelerations to the moving links, but they do not contribute to supporting their weight. A mechanism is said to be *dynamically balanced* if both the resultant vector (*shaking force*) and the resultant moment about an arbitrary pole (*shaking moment*) of inertia forces are equal to zero; in this case, only the gravity load of the moving links is transmitted to the fixed base. The shaking force vanishes if the overall centre of mass (c.o.m.) of the mechanism is stationary; the shaking moment is naught if the total angular momentum remains constant (the vanishing of the shaking force is, in this case, a necessary requisite). Since complete dynamic balancing is hardly achievable in practice – the introduction of rotating inertias being generally required – only the shaking force is often compensated; in this case, the mechanism is simply said to be *force balanced*. Depending on the type of balancing strategy adopted, different advantages may be potentially achieved [1]:

- a less onerous and more uniform loading of the actuators due to lower force/torque requirements induced by gravity and/or inertia forces, resulting in enhanced energy efficiency and a need for lighter and less powerful motors;
- undersizing of brakes (needed to maintain an unbalanced mechanism at rest when the motors are turned off), leading to further weight saving and better efficiency;
- reduction of vibrations and wear induced by base-transmitted unbalanced forces.

The present research focuses on two very common strategies for gravity compensation, namely *mass* and *elastic balancing*. Following the first technique, mass is conveniently redistributed within the mechanism in order to keep its c.o.m. stationary, so that the gravitational potential energy remains constant; this technique often requires adding counterweights in proper locations. By the second strategy, elastic elements are introduced in the system in such a way that the total potential energy, in this case given by the sum of gravity and elastic contributions, is invariant.

The main advantages of mass balancing consist in that it leads to force-balanced mechanisms (the shaking force vanishes, since the overall c.o.m. is stationary) and gravity compensation is assured for any orientation (and magnitude) of the gravity vector with respect to the fixed frame. As a consequence, the balanced mechanism may be installed with arbitrary orientation. On the other hand, mass balancing presents the following drawbacks:

- counterweights augment the total weight and bulkiness of the system;
- mass increment generates higher inertia, which requires greater actuator power and it may lead to larger-size motors (limiting one of the most important benefits provided by gravity compensation);
- in the absence of driving or braking forces at the rest position, a variation of the payload relative to the designed value makes the mechanism uncontrollably move.

The above drawbacks may severely limit or even overcome potential advantages. Optimum results are naturally expected when balancing is obtained by simple redistribution, rather than addition, of internal mass, since no counterweights are adjoined [2, 3].

Elastic balancing, conversely, does not eliminate the shaking force and it guarantees gravity compensation for only one direction and magnitude of the gravity vector (that is to say, for only one orientation of the mechanism). However, the following benefits usually result:

- little weight and inertia are normally added to the system;
- a decrease of all driving torques is usually achieved (even though this may be accompanied by a raise of bearing forces);