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Optimum dynamic balancing of planar parallel manipulators based on sensitivity analysis

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Abstract

This paper addresses the optimum dynamic balancing of planar parallel manipulators exemplified with a 2 DOF parallel manipulator articulated with revolute joints. The dynamic balancing is formulated as an optimisation problem such that while the shaking force balancing is accomplished through analytically obtained balancing constraints, an objective function based on the sensitivity analysis of shaking moment with respect to the position, velocity and acceleration of the links is used to minimise the shaking moment. Sets of optimisation results corresponding to various combinations of the elements of the objective function are evaluated in order to quantify their influence on the resulting shaking moment, ground forces and the driving torques. The results prove that the proposed optimisation approach can be used to completely eliminate the shaking force and to minimise the shaking moment transmitted to the frame of the parallel mechanism. For parallel manipulators or mechanisms with higher degrees of freedom, for which it is virtually impossible to obtain shaking force balancing conditions analytically, we propose an alternative constrained optimisation procedure. This procedure is based on the fact that while the magnitude of either the shaking force or the shaking moment can be bounded through including a set of constraints in the optimisation algorithm, the sensitivities of the other, either those of the shaking force or the shaking moment, can be minimised.

Keywords: Dynamic balancing; Parallel manipulators; Optimal mechanism design

1. Introduction

When designing high-speed mechanisms such as a parallel manipulator, a special attention should be paid to the inertia-induced force (shaking force) and moment (shaking moment) transmitted to the mechanism frame. If their magnitudes and directions change throughout the operation of the mechanism, the mechanism will vibrate undesirably, and consequently, its dynamic performance will be unsatisfactory. Therefore, the

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main concern is either to completely eliminate them or to ensure that their magnitudes and directions do not change significantly. If the former is realised, such a mechanism is said to be dynamically balanced. It is virtually impossible to have the former realised without increasing the number of moving links of a mechanism. The latter can be partly realised by taking certain precautions such as minimising the magnitudes of the shaking force and shaking moment, and if possible constant, using a constrained optimisation procedure. In fact, it is a common practice to employ a constrained optimisation procedure in selecting the balancing parameters of a mechanism to ensure that (i) the magnitudes of the ground/bearing forces and the driving torques and (ii) the shaking moment are minimised [1–5]. In this study, we deviate from this common practice such that we choose an objective function which satisfies the second (ii) objective through minimizing sensitivities of the shaking moment to the position, velocity and acceleration of a planar parallel manipulator, which is a revolute-jointed 5-bar mechanism [6–8], rather than targeting directly at minimizing the magnitude of the shaking moment. The motivation behind our approach is that making the shaking moment robust (or less sensitive) to uncertain parameters such as the trajectory to be followed by the mechanism also minimises the shaking moment. In fact, when the results of this approach to optimum dynamic balancing are compared to those of the traditional way of directly minimizing the magnitude of the shaking moment [5], it is found that the sensitivity analysis based shaking moment minimisation is more effective in reducing the shaking moment. Three sets of optimisation results presented prove that the proposed optimisation approach can be used to completely eliminate the shaking force and to minimise the shaking moment transmitted to the frame of the parallel mechanism. For parallel manipulators or mechanisms with higher degrees of freedom (>2), for which it is virtually impossible to obtain shaking force balancing conditions analytically, we propose an alternative constrained optimisation procedure. This procedure is based on the fact that while the magnitude of either the shaking force or the shaking moment can be bounded through including a set of constraints in the optimisation algorithm, the sensitivities of the other, either those of the shaking force or the shaking moment, can be minimised through the objective function. The reason why we consider a planar parallel manipulator in this study is to use three of such a planar mechanism to build a 6 degree of freedom (DOF) parallel manipulator articulated with 6 single degree of freedom joints whose production, assembly and maintenance are simpler than those of multi-degree of freedom joints such as universal and spherical pairs [15]. It must be kept in mind that it is virtually impossible to dynamically balance a 6 DOF mechanism as a whole.

With reference to the literature on balancing of mechanisms, there has been a considerable amount of research devoted to the dynamic balancing of single degree of freedom mechanisms [9–13], static balancing of planar and spatial parallel manipulators [14,15], and optimisation procedures based on the minimisation of the shaking force and moment transmitted to the ground, bearing forces, and driving torques of the mechanisms, predominantly single degree of freedom mechanisms [1–3,12,16–18]. However, very little has been published on the optimum dynamic balancing of multi-degree of freedom mechanisms such as parallel manipulators [5,19]. Recently, Gosselin et al. [19] have proposed a methodology based on minimising the sum of the moving masses of a 4-bar mechanism to design a ‘reactionless’ 3 DOF parallel mechanism. Based on the 4-bar mechanism, they have synthesised 2 DOF mechanisms and then utilised three of them to synthesise a 3 DOF parallel mechanism. Wiederrich and Roth [20] presented general conditions to determine the mass distribution parameters of 4-bar mechanisms operating in the horizontal plane, based on the linear momentum and angular momentum balancing. It was assumed that the mass of the mechanism could be represented with a point mass, without any mass moment inertia about the mass center. Conte, George, Mayne, and Sadler [4] reported on a balancing method that combined kinematic synthesis, dynamic design, and input speed trajectory design to reach the trade-off of dynamic balance and to satisfy the kinematic requirements and constraints simultaneously for 4-bar linkages. Feng [21] have used a combination of mass distribution and the addition of two types of the inertia counterweights in order to realise the dynamic balancing of a number of single degree freedom mechanisms. Arakelian and Dahan [22] studied the shaking force and shaking moment balancing of a 4-bar mechanism and a spatial RSSR mechanism by minimizing the RMS value of the shaking moment. Recently, Arakelian and Smith [23] have reported on dynamic balancing of single degree of freedom mechanisms by using the counterweights movement of a pantograph mechanism, which is formed by adding a minimum number of links to the original mechanism. Xi [24] have reported on the dynamic balancing of a 6 DOF parallel manipulator using a dynamic condition index based on the isotropy and constancy of a generalised inertia matrix. The dynamic balancing is defined as the minimisation of the