SHAKING FORCE AND MOMENT BALANCING IN MECHANISMS - A REVIEW

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Abstract

This paper reviews the various methods developed for balancing of the planar mechanisms. The methods used for complete force balance as well as complete force and moment balances are reviewed.

Index Terms: Dynamic balancing, Shaking force, Shaking moment

I. COMPLETE SHAKING FORCE BALANCING

The complete shaking force balancing known as static balancing requires the total center of mass of a mechanism to be fixed. The two common approaches used to achieve this are the redistribution of the link masses and use of the counterweights for the mechanism links.

The analytical methods have been developed to trace and keep the total mass center of the mechanism fixed. Shchepetilnikov [1] presented the method of '*Principal Vectors*' in which the position of the mass center is described using the vectors directed along the links of the mechanism. Similarly, Berkof and Lowen [2] introduced the '*Method of Linearly Independent Vectors*' for the complete force balancing of four and six-bar planar mechanisms with arbitrary link mass distribution (Fig. 1). The balancing conditions are presented for the internal mass redistribution and for the counterweight addition. In this method, the links masses are redistributed in such a way that it eliminates the time-dependent terms coefficients in an equation representing the trajectory of the total center of mass of the mechanism.

This results in a fixed center of mass of the mechanism and thus the complete shaking force balancing is achieved.

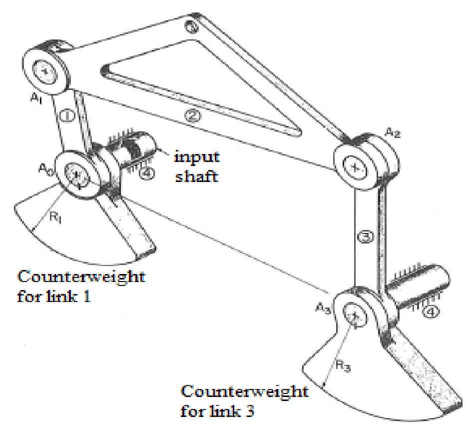

Fig. 1 Complete force balancing of planar four-bar mechanism using counterweights [2]

Tepper and lowen [3] extended this method and proved that the counterweights required for the complete force balance of an *n*-link planar mechanism are half of the total number of the links. They developed the '*Contour Theorem*' to differentiate between the mechanisms which can be fully force balanced and those which cannot. Contour theorem examines the nature of the paths from the individual links to the ground. It was found that the pinned planar mechanisms can always be force balanced as they do not have time-dependent coefficient in the center of mass equation. Based on the same approach, Walker and Oldham [4], [5] presented the complete force balancing conditions for various types of planar mechanisms with multi-degrees of freedom. The counterweights are used to balance the mechanism containing both the revolute and the prismatic joints. They presented the criteria for deciding the number of the counterweights required for complete force balancing and for the selection of the links to which the counterweight are to be attached. As an extension of the method proposed by Berkof and Lowen [2], Kochev [6] used the ordinary vector algebra for deriving the conditions for full force balancing in the planar mechanisms. Thus, the linear balancing conditions are presented in the Cartesian form in this method. A computer program is also developed to completely balance the shaking force in the mechanisms based on the *Method of Linearly Independent Vectors* which also controls the increment in the shaking moment through properly designing the counterweights [7]. In another approach, the balancing conditions are presented to reduce the root-mean-square (RMS) and maximum value of the shaking force in the mechanisms which is known as the best uniform balancing [8].

Chiou and Davies [9] minimized the shaking force in a press machine by designing a cam mechanism. Force balancing along with the trajectory tracking is achieved in a five-bar real-time controllable (RTC) mechanism using the adjusting kinematics parameter (AKP) approach [10], [11]. Similar to the robot manipulators, the RTC mechanism is driven by the servomotors and can be scheduled and planned in real-time. The AKP approach was found better than the counterweight method as far as the reduction in the servomotors torques and joint forces are concerned.

The effect of the complete force balance on the other dynamic properties was studied by Kamenskii [12] and Lowen et al. [13]. It was found that the complete force balance increases the shaking moment and driving torque for the mechanism. Therefore, only force balancing is not useful and the moment balance is also needed to balance the mechanism completely.

II. COMPLETE SHAKING FORCE AND SHAKING MOMENT BALANCING

To achieve the dynamic balance in the mechanisms, the shaking moment is completely balanced by eliminating the angular momentum of the moving links along with the full force balance. The complete elimination of the total angular momentum using the link mass distribution and/or adding the counterweights is not possible [14]. Therefore, normally the shaking moment is reduced by adding disk counterweights [3], [14] – [17], cam-actuated oscillating counterweight [18], physical pendulum [19], counter-rotating disks [20], inertia counterweight [21], [22], geared counterweights [23], [24], duplicate mechanism [25] and moment balancing idler loops [26]. Moore et al. [27] presented the different sets of the design parameters that dynamically balance a four-bar mechanism without using the counter-rotations.

Berkof [19] developed a method in which the coupler mass is dynamically substituted by the concentrated masses located at the rotating links to completely balance the force and moment in the mechanisms. In this method, the coupler is treated as a massless link having two concentrated masses and thus only the rotating links need to be balanced for complete balancing of the mechanism. Considering the dynamic replacement of point masses for the moving links described as the mass flow concept, the complete balancing of the planar mechanisms can be obtained [24].

As an extension to the method of linearly independent vectors for full force balance, Elliot and Tesar [28], [29] presented a theory to balance shaking force and shaking moment in the complex planar mechanisms. Esat and Bahai [23] extended the method developed by Tepper and Lowen [3] and found that for a fully force balanced mechanism; the moment can be completely eliminated using the geared counter-inertias (Fig. 2). Kochev [30] suggested the balancing of the shaking moment in a force balanced mechanism by prescribing the input speed fluctuations using non-circular gears.

Kamenskii [12], [18] used the cam mechanism to completely balance the shaking force and shaking moment in the planar mechanisms (Fig. 3). The reduction of the inertia forces is achieved by using a cam-counterweight arrangement where the cam driven masses keep the mechanism's center of mass fixed.

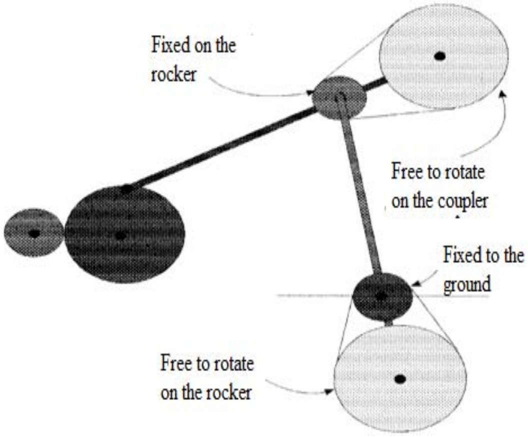

Fig. 2 Complete balancing of planar four-bar mechanism using geared counter-inertias [23]

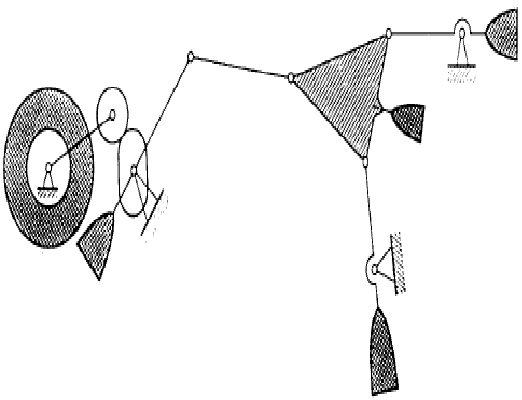

Fig. 3 Dynamic balancing of planar six-bar mechanism using cam operated counterweight [12], [18]

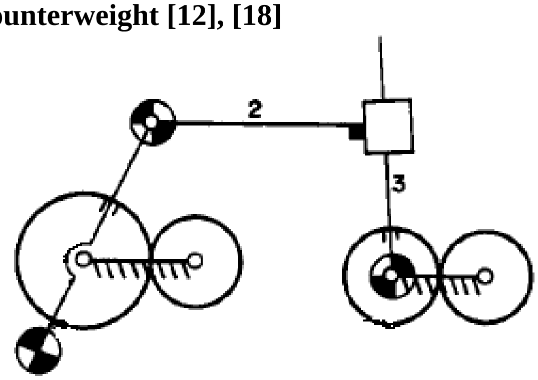

Fig. 4 Complete shaking force and shaking moment balancing through mass redistribution and addition of inertia counterweights [15]

Feng [15], [16] developed a method for complete force and moment balance of the planar mechanisms combining mass redistribution and addition of the geared inertia counterweights (Fig. 4). The analytical conditions for complete force and moment balance for 17 types of eight-bar mechanism and 26 types of four-, five- and six-bar mechanism with prismatic pairs are presented in this method.

Arakelian and Smith [25], [31] proposed a method to completely balance the planar mechanisms using the counterweights connected through toothed-belt transmission system and gears. This arrangement generates an equal and opposite movement to mechanism's center of mass movement and hence completely balance the mechanism (Fig. 5). Similarly, Arakelian [32] presented a method to improve the balancing of a double slider-crank mechanical system (Fig. 6). The shaking force is balanced in this method by using the two slider-crank mechanisms having equal and opposite movements. The shaking moment is balanced in this mechanism by the design modification of the second connecting rod of the double slider-crank mechanical system.

Arakelian and Briot [33] used counterweight with cam mechanism to balance a slider-crank mechanism. The torque reduction in this mechanism is achieved through the spring that is used to maintain contact with the balancing cam mechanism.

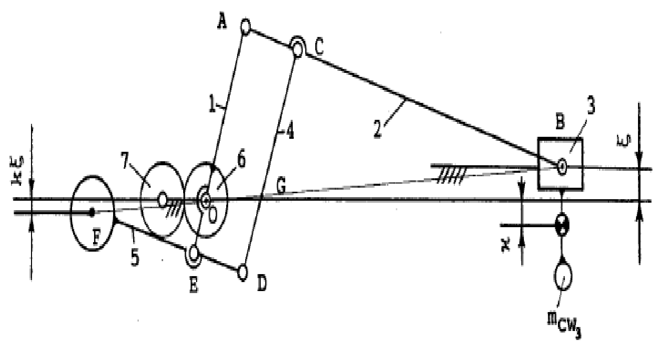

Fig. 5 Complete shaking force and shaking moment balancing of slider-crank mechanism based on the copying properties of the pantograph [25]

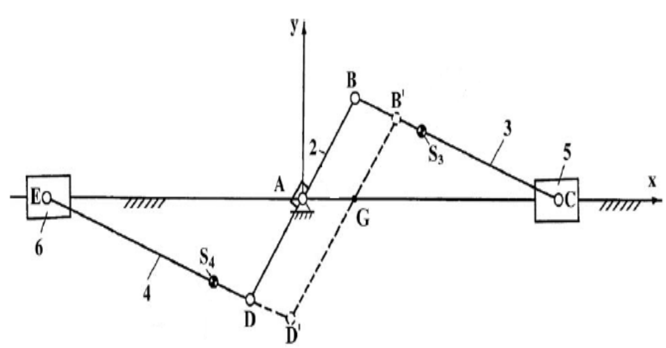

Fig. 6 Self-balanced slider-crank mechanism [32]

Bagci [26], [34] solved the balancing problem of planar mechanisms containing multiple prismatic pairs that cannot be fully force balanced using the balancing criteria presented by Tepper and lowen [3]. He termed it as “force transmission irregularities” and used the “idler loop” concept with counter-rotating disks to completely balance the force and moment in the mechanism. Dresig and Dien [35] proposed a method to completely balance the shaking force and shaking moment using a single rigid body known as the *balancing body*. In this method, the inertia forces and moments both for the mechanism and the balancing body are eliminated by controlling the motion of the balanced body.

Gosselin et al. [36] proposed an analytical method for static and dynamic balancing in the mechanisms. In this method, the balancing conditions are presented by the algebraic equations using joint angular velocities and complex variables. Thus, by using the computer algebra, the necessary and sufficient conditions are derived to completely balance the shaking force and shaking moment in the mechanism.

The effects of the dynamic balancing on the elastodynamic properties of the mechanisms are investigated in [37] – [40]. It is found that these methods increase the overall mass, space, cost and complexity in the mechanisms, and most of them are applicable to the simple mechanisms only. Hence, complete force and moment balancing is achieved by producing shaking moment that counteract the moment in the original mechanism.

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