World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:15, No:6, 2021

Shaking Force Balancing of Mechanisms: An Overview

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***Abstract*—**The balancing of mechanisms is a well-known problem in the field of mechanical engineering because the variable dynamic loads cause vibrations, as well as noise, wear and fatigue of the machines. A mechanical system with unbalance shaking force and shaking moment transmits substantial vibration to the frame. Therefore, the objective of the balancing is to cancel or reduce the variable dynamic reactions transmitted to the frame. The resolution of this problem consists in the balancing of the shaking force and shaking moment. It can be fully or partially, by internal mass redistribution via adding counterweights or by modification of the mechanism's architecture via adding auxiliary structures. The balancing problems are of continue interest to researchers. Several laboratories around the world are very active in this area and new results are published regularly. However, despite its ancient history, mechanism balancing theory continues to be developed and new approaches and solutions are constantly being reported. Various surveys have been published that disclose particularities of balancing methods. The author believes that this is an appropriate moment to present a state of the art of the shaking force balancing studies completed by new research results. This paper presents an overview of methods devoted to the shaking force balancing of mechanisms, as well as the historical aspects of the origins and the evolution of the balancing theory of mechanisms.

***Keywords*—**Inertia forces, shaking forces, balancing, dynamics.

I. Introduction

FROM very ancient times, when construction work was widely carried out, various auxiliary technical means appeared in which various simple mechanisms were used. The experience of the developers of such mechanisms has shown that in many cases, when moving heavy objects, there was a need to compensate the moving masses by additional means. Since for a long time the driving force in machines was the human physical force, the creation of additional balancing means was considered. It was an important technical problem that would raise the payload capacity of machines. At that time, the speeds of the payloads were very low and the creators carried out the gravitational force balancing of machines. The design methods of such machines were based on intuition and simple arithmetic calculations. The situation began to change at the beginning of the last century. With the appearance of the first steam machines and, particularly, of internal combustion engines, it became evident that the fast moving elements of machines bring about unwanted effects, such as vibration and noise. The explosive growth of high speed machines presented engineers with the problem of creating the theoretical bases for the mechanism balancing. The problem of balancing gravitational forces became insufficient and it was transformed into the problem of the inertia force balancing. Thus, in the new context, the problem of mechanism balancing was formulated as follows: determination of such redistribution of moving masses of the mechanism that will provide small dynamic loads on the frame of the mechanism. Thus, two main types of balancing appeared: force balancing (static balancing) - when the shaking force is cancelled, and dynamic balancing - when the shaking force is cancelled together with the shaking moment.

It is necessary to indicate here that in the theory of balancing the term “static balancing” should be interpreted differently and has nothing with the well-known mechanical phenomenon of “static nature” (that is, when there is no movement). By its nature, “balancing of mechanisms” is a dynamic phenomenon, and unbalanced forces are the result of accelerated movement of the mechanism's links. However, the balancing of shaking forces was called «static», as one can detect the existence of these forces in static mode, i.e., the imbalance of the shaking force in any mechanism can be experimentally revealed in a static state without the need to drive the links of the mechanism. With regard to the imbalance of the shaking moment, it can be detected during mechanism motion only, i.e., in the dynamic mode. The term “static balancing” has lost its original meaning in the theory of balancing mechanisms. Nowadays, the term “balancing shaking forces” is widely used. The term "static balancing" is most often used when considering the balancing problems of rotating bodies.

Let us consider the methods of shaking force balancing of mechanisms.

II. Shaking Force Balancing of Mechanisms

One of the first works in the field of mechanism balancing is Fisher's study [1], in which a method called the “principal vector method” was proposed. The goal of this approach was to study the shaking force balancing of the mechanism relative to each moving link and in the determination of those points on the moving links relative to which a static balance was reached. Author called these points as «principal points». Then, from the condition of similarity of the vector loop of the principal points and the mechanism's structural loop, the conditions of the shaking force balancing were derived. It was shown that for complete shaking force balancing it is necessary that the common center of masses of the moving links of the mechanism must be motionless. This method was used in [2]-[4]. At the

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time, it was of a significant importance as it allows one to create various auxiliary devices intended for studying the motion of the centers of moving masses of mechanisms. This method has been successfully used for determination of the mass centers of mechanisms [5], for balancing of mechanisms with unsymmetrical links [6] and for shaking moment balancing of three elements in series [7]-[9].

Another widely used balancing method, which was one of the firsts, was the "method of static substitution of masses". Its goal was to statically replace the mass of the connecting rod by concentrated masses, which are then balanced together with the rotating links. This approach allows one to change the problem of mechanism balancing into a simpler task of balancing rotating links. It was developed in [10]-[13].

Another tendency in the shaking force balancing theory was the method of «*duplicated mechanism*» [14]-[17]. The addition of a duplicate mechanism to any given mechanism makes the new combined center of mass stationary. This approach has led to the creation of self-balancing mechanical systems. The opposite motion permitting to carry out the shaking force balancing has also been used in [18]-[25].

From the beginning of the 20's of the last century special attention was paid to balancing of engines [26]-[31] and mechanisms in agricultural machines [32], [33]. Engineers successfully used the «Lanchester balancer» [34]. It should be noted here that the «Lanchester balancer» remains classic and practical even today. In many cars, to balance the shaking forces in four-stroke engines, opposed rotating shafts are used in four-cylinder in-line engines. The added shafts are synchronized with the crankshaft rotation by means of a geared belt drive. These added shafts for balancing the second harmonic of inertia forces are designed in the same way as in the «Lanchester balancer». This approach has been investigated in [35] in order to minimize the shaking moment and in [36] for shaking force minimization in offset crank–slider mechanisms (Fig. 1). The shaking force of the off-set slider-crank mechanism is provided by two terms: the first term is the primary shaking force and the second is the secondary shaking force. The first order of shaking forces is balanced by counterweights that rotate at the input crankshaft speed but are out of phase with the input crankshaft by an angle α (see Fig. 1). This angle has been determined taking into account the slider's eccentricity. The second order of shaking forces is balanced by counterweights that rotate at two times the input speed.

Kamenskii [37] first used the cam mechanism for balancing of planar linkages. In his study, the balancing of inertia forces was achieved by means of a cam bearing a counterweight. It was revealed how cam-driven masses may be determined to keep the total center of mass of a mechanism motionless. The solution proposed by Kamenskii found further development in [38]. A new design concept permitting the simultaneous shaking force/shaking moment balancing and torque compensation in slider-crank mechanisms was developed. In mentioned work, at first, the shaking force and shaking moment have balanced via a cam mechanism carrying a counterweight. Then, the spring designed for maintaining contact between the cam and the follower is used for torque minimization. The cam mechanisms for shaking force minimization in press machines were studied in [39].

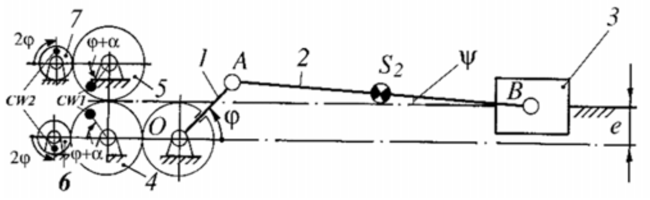

Fig. 1 Generalized Lanchester balancer for shaking force balancing of off-set crank-slider mechanisms

In Hilpert's study [40], a pantograph mechanism is adapted for the displacement of the counterweight. This method was further used in [41]-[43], in which the duplicating properties of the pantograph are used by adding to the balancing mechanism a two-link group forming a parallelogram pantograph. For example, for the shaking force balancing of a slider-crank mechanism, the added two-link group forms a pantograph with the crank and coupler of the initial mechanism. The formed pantograph system accomplishes a rectilinear translation that is opposite to the movement of the slider. Please note that the pantograph system may be formed by gears or by toothed-belt transmission carrying a counterweight. Such a solution allows the balancing of mechanisms with a smaller increase of link mass compared to earlier methods.

In the 40's of the last century partial balancing methods based on function approximation, were successfully developed. Such a solution was proposed by [44], [45]. In these works, the balancing conditions are formulated by minimization of root-mean-square (r.m.s.) or maximal values (Chebichev approach) of shaking force and called «best uniform balancing» of mechanisms. This approach has been used in [46] and [47]. A similar study has been developed in [48].

The use of the slider-crank mechanism in internal combustion engines brought about the rapid development of methods based on harmonic analysis. The minimization of inertia effects is accomplished by the balancing of certain harmonics of the shaking forces and shaking moments. Unbalanced shaking forces and shaking moments are decomposed into Fourier series (or Gaussian least-square formulation) and then balanced separately. This solution found wide applications as it can be implemented by means of rotating counterweights connected to the input crank.

The shaking force harmonics of slider-crank mechanisms were investigated and a large number of studies on the problem of balancing engines and clutches were published. Certain references should be mentioned [49]-[58]. The properties of the Watt-gear slider-crank mechanism has been used for balancing [59].

In [60] was shown that by coupling of two Oldham mechanisms, a balancer can be obtained for the cancellation of second-harmonic shaking forces or shaking moments. The advantage of this balancer is that it operates at the speed of the machine to be balanced while the Lanchester type balancer must operate at two times the primary speed to achieve the same balancing effect. The harmonic balancing has also been applied in [61] in order to found that there are boundaries to the regions where additional shafts can be located.

In 1968, Berkof and Lowen [62] developed a new approach for shaking force balancing of mechanisms. It was called the method of «linearly independent vectors». In the mentioned method, the vector equation describing the position of the mechanism's center of masses is treated in conjunction with its closed loop equation. As a result, it was obtained an equation of static moments of moving link masses inclosing single linearly independent vectors. From the conditions for shaking force balancing, the parameters of the balanced mechanism were obtained by reducing the time-dependent coefficients to zero. This method found further development and applications in [63]-[69]. In [67], an interactive computer program was proposed, which allows one to design fully force balanced four-bar linkages by the mentioned method. The increase in the shaking moment of these linkages is optimized by using the counterweight such that the shaking moment of the mechanism is made as small as possible.

Reference [70] deals with a new balancing approach based on the optimal trajectory planning of the common center of mass of the manipulator. The goal of the proposed balancing method is the following: the manipulator is controlled not by applying gripper's trajectories but by path planning the displacements of the manipulator's center of masses. The trajectories of the total mass center of all moving links of the manipulator are defined as a straight line between the initial and final positions of the gripper. Then, the motion between these two positions is carried out with "bang-bang" law. Such a generation of motion allows the reduction of the maximal value of the mass center acceleration and, consequently, leads to the decrease of the shaking force. This method found further development in [71]-[77].

III. Conclusion

Despite its ancient history, mechanism balancing theory continues to develop and new solutions are constantly being reported. Particular attention is paid to methods that take into account physical aspects such as the elasticity of links and the clearance in the joints of the mechanisms. The development of new software such as ADAMS creates a base for a more realistic representation of the mentioned physical effects.

In conclusion, it should be noted that the strict space limitations did not permit the inclusion in this overview of methods devoted to the shaking moment balancing. In the future, we will make all possible efforts to present a similar overview devoted to shaking moment balancing.

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