Chapter 2
An Overview of Balancing Methods

Abstract The review of state-of-the-art literature including more than 500 references is given in this chapter. The balancing methods illustrated via various kinematic schemes are presented in three main parts: shaking force and shaking moment balancing of linkages; shaking force and shaking moment balancing of robots and manipulators, as well as gravity balancing used in robotics. We consider that such participation reflects the particularities of the reviewed balancing methods and their specific characteristics.

2.1 Shaking Force and Shaking Moment Balancing of Linkages

The balancing of mechanisms is a well-known problem in the field of mechanical engineering because the variable dynamic loads cause noise, wear and fatigue of the machines. The resolution of this problem consists in the balancing of the shaking force and shaking moment, fully or partially, by internal mass redistribution or by adding auxiliary links.

From very ancient times, with building works that were widely carried out, different auxiliary technical means appeared in which various simple mechanisms were used. The practical experience of the creators of such mechanisms showed that in many cases, during the displacement of heavy objects, the necessity arose for compensation of moving masses by additional means. Since for a long time the driving force of such mechanical systems was human physical force, the creation of additional balancing means was considered to be a significant technical problem that would increase the hoisting capacity of mechanisms. At that time, the speeds of the objects to be displaced were very low and the inventors simply confined themselves to balancing gravitational forces of mechanism links. The design methods of such mechanisms were based on intuition and the simplest arithmetical computations. The situation began to change at the beginning of the last century. With the emergence of the first steam machines and, particularly, of internal combustion engines, it became evident that the fast moving elements of machines brought about undesirable effects, such as vibration, noise and rapid wearing. The explosive growth in the production of high speed mechanisms presented scientists with the problem of creating the theoretical principles for the balancing of mechanisms. The problem of balancing

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gravitational forces ceased to be critical and was transformed into the problem of balancing the inertia forces of mechanisms. This problem may be formulated as follows: determination of parameters, redistribution of the rapidly moving mechanism masses that will provide small dynamic loads onto the mechanism foundation. Two main types of balancing have emerged: static—when the shaking force is cancelled, and dynamic—when the shaking force is cancelled together with the shaking moment.

Here, we point out that in the theory of balancing, the term “static balancing” should be understood arbitrarily and has nothing in common with the well-known mechanical phenomenon of “static character” (i.e. when there is no motion). By its character, “balancing of mechanism” is a dynamic phenomenon and any imbalance is the result of an accelerated motion of mechanism links. However, the mode of balancing the shaking force was called “static”, as imbalance of shaking force can be detected in static conditions, i.e. imbalance of shaking force in any mechanism can be demonstrated experimentally in the static state, without the links having to be driven, while imbalance of the principal moment of inertia may be revealed during mechanism motion only, i.e. in the dynamic behavior.

The term “static balancing” has almost fallen out of use now in the theory of balancing of mechanisms. Now, the term “shaking force balancing” is well known. The term “static balancing” is most often applied when considering the balancing problems of rotating bodies, for example rotors, turbines, etc.

First, let us consider the methods of shaking force balancing of linkages.

2.1.1 Shaking Force Balancing of Linkages

One of the first publications in this field may be considered to be the work of O. Fischer (Fischer 1902) in which a method called the method of “principal vectors” was suggested. The aim of this approach was to study the balancing of the mechanism relative to each link and in the determination of those points on the links relative to which a static balance was reached. These points were called “principal points”. Then, from the condition of similarity of the vector loop of the principal points and the structural loop of the mechanism, the necessary conditions of balancing were derived. It was thereby shown that the necessary and sufficient condition for balancing the shaking force is the fixation of the common centre of masses of the moving links of the mechanism. This method was used in the works of V. P. Goryachkin (Goryachkin 1914), Kreutzinger (Kreutzinger 1942), V. A. Yudin (Yudin 1941). At that time, it was of a particular importance as it served to create several auxiliary devices intended for studying the motion of the centres of mechanism masses. This method was also used for determination of the mass centers of mechanisms (Shchepetilnikov 1968), for balancing of mechanisms with unsymmetrical links (Shchepetilnikov 1975) and for shaking moment balancing of three elements in series (van der Wijk 2013; van der Wijk and Herder 2012, 2013).

Another well known method for balancing which was one of the first that was developed, was the “method of static substitution of masses”. Its aim was to statically substitute the mass of the coupler by concentrated masses, which are balanced thereafter together with the rotating links. Such an approach allows changing the problem of mechanism balancing into a simpler problem of balancing rotating links. It was used in the works of F. R. Grossley (Grossley 1954), R. L. Maxwell (Maxwell 1960), M. R. Smith and L. Maunder (Smith and Maunder 1967), G. J. Talbourdet and P. R. Shepler (Talbourdet and Shepler 1941).

From the beginning of the 1920s, special attention was paid to balancing of engines (Cormac 1923; Dalby 1923; Delagne 1938; Doucet 1946; Kobayashi 1931; Lanchester 1914; Root 1932) and mechanisms in agricultural machines (Artobolevsky and Edelshtein 1935; Artobolevsky 1938). Engineers successfully used the “Lanchester balancer” (Lanchester 1914). It should be noted here that the principle proposed by Lanchester remains classic and practical even today. In modern cars, to balance the inertia forces in four-stroke engines, opposed balancing shafts are used in four-cylinder in-line engines, these shafts being synchronized with the crankshaft by means of a geared belt drive. These balancing shafts for balancing the second harmonic are designed in the same way as in the “Lanchester balancer”. This approach has been investigated in (Chiou and Davies 1994) in order to minimize the shaking moment and in (Arakelian and Makhsudyan 2010) for shaking force minimization in offset slider-crank mechanisms.

Another trend in the balancing theory was developed by means of the “duplicated mechanism” (Arakelian 2006; Artobolevsky 1977; Davies 1968; Kamenski 1968b). The addition of an axially symmetric duplicate mechanism to any given mechanism will make the new combined centre of mass stationary. This approach resulted in the building of self-balancing mechanical systems. The principle of construction of self-balanced mechanical systems is to have two identical mechanisms executing similar but opposite movements. The opposite motion for shaking force balancing has also been used in (Berkof 1979a; Doronin and Pospelov 1991; Dresig 2001; Dresig and Holzweißig 2004; Filonov and Petrikovetz 1987; Frolov 1987; Turbin et al. 1978; van der Wijk and Herder 2010b).

The known kinematic diagrams of self-balanced systems are shown in Fig. 2.1. They can be arranged into three groups: (a) the systems built by adding an axially symmetric duplicate mechanism with separated input cranks (a1–a3); (b) the systems built by adding an axially symmetric duplicate mechanism with common input crank (b1–b6); (c) the systems built via an asymmetric model of duplicate mechanisms (c1–c3). Such mechanical systems were used successfully in agricultural machines, mills and in various automatic machines.

V. A. Kamenski (Kamenski 1968a) first used the cam mechanism for the balancing of linkages. In his work, the variation of inertia forces was performed by means of a cam bearing a counterweight and it was shown how cam-driven masses may be used to keep the total centre of mass of a mechanism stationary. This approach was further developed in (Arakelian and Briot 2010), in which a design concept permitting the simultaneous shaking force/shaking moment balancing and torque compensation in slider-crank mechanisms has been proposed. First, the shaking force and shaking

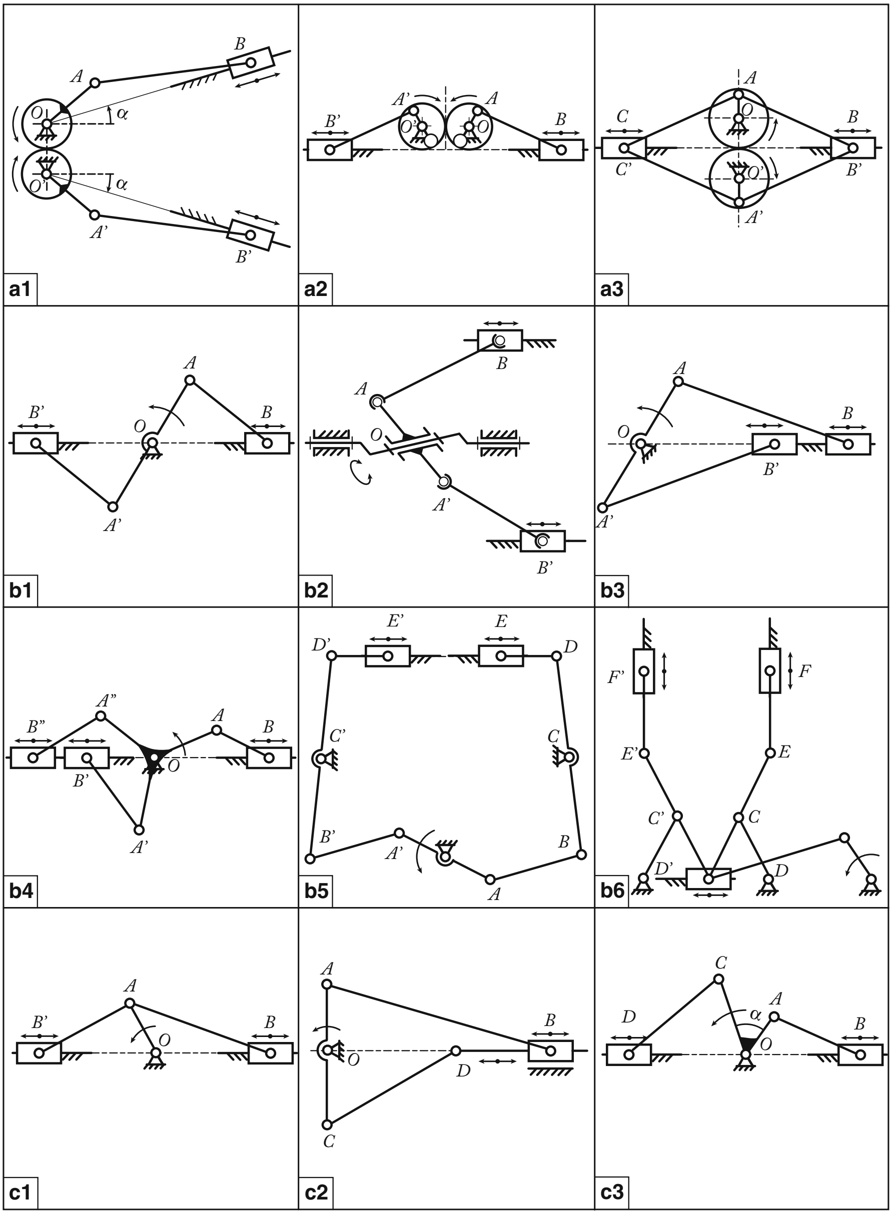

Fig. 2.1 Kinematic diagrams of self-balanced systems

moment have been cancelled via a cam mechanism carrying a counterweight. Then, the spring designed for maintaining contact in this balancing cam mechanism is used for torque minimization. The designs of cam mechanisms for shaking force minimization in press machines have been investigated in (Chiou and Davies 1997).

Among several works, the study of H. Hilpert (Hilpert 1968) in which a pantograph mechanism is used for the displacement of the counterweight may also be distinguished. This approach was further developed in works (Arakelian 1993, 1998b; Arakelian and Smith 2005c) in which the duplicating properties of the pantograph are used by connecting to the balancing mechanism a two-link group forming a parallelogram pantograph with the initial links. For example, for the balancing of a slider-crank mechanism, the additional two-link group forms a pantograph with the crank and coupler of the initial mechanism. The formed pantograph system executes a rectilinear translation that is opposite to the movement of the slider. Thus a new solution of a self-balanced mechanical system without any additional slider (prismatic) pair is proposed. The pantograph system may be formed by gears or by toothed-belt transmission carrying a counterweight. Such an approach permits the balancing of mechanisms with a smaller increase of link mass compared to earlier methods.

In the 1940's, partial balancing methods based on function approximation were successfully developed. Such a solution was proposed by Y. L. Gheronimus (Gheronimus 1968a, b). In these works, the balancing conditions are formulated by the minimization of root-mean-square (*rms*) or maximal values (Chebichev approach) of shaking force and they are called "best uniform balancing" of mechanisms. This approach has been used in (Arakelian 1995) and (Arakelian 2004a). A similar study has been developed in (Han 1967).

The use of the slider-crank mechanism in internal combustion engines brought about the rapid development of methods based on harmonic analysis. The reduction of inertia effects is primarily accomplished by the balancing of certain harmonics of the forces and moments. Unbalanced forces and moments are divided into Fourier series (or Gaussian least-square formulation) and then studied by parts. This solution found a large application as it may be realized by means of rotating balancing elements connected to the crank.

The force harmonics of slider-crank mechanisms of various types were examined and a large quantity of works concerning the problem of balancing of engines and linkages was published. We would like to note certain references (Emöd 1967; Gappoev 1979; Gappoev and Tabouev 1980; Gappoev and Salamonov 1983; Innocenti 2007; Semenov 1968b; Stevensen 1973 ; Tsai and Maki 1989; Urba 1978, 1980). The properties of the Watt-gear slider-crank mechanism which are similar to harmonics has also been used in order to solve the balancing problem (Arakelian and Smith 2005a).

In (Tsai 1984), it was shown that by a proper arrangement of two Oldham couplings, a balancer can be obtained for the elimination of second-harmonic shaking forces or second-harmonic shaking moments or a combination of both shaking forces and moments. The advantage of this balancer is that it runs at the primary speed of the machine to be balanced whereas the Lanchester-type balancer must run at twice the primary speed to achieve the same balancing effect. The harmonic balancing has also been applied in (Davies and Niu 1994) in order to find that there are boundaries to the regions where additional shafts can be located.

In 1968, R. S. Berkof and G. G. Lowen (Berkof and Lowen 1969) proposed a new solution for shaking force balancing of mechanisms that is called the method of "linearly independent vectors". In this method, the vector equation describing the position of the centre of total mass of the mechanism is treated in conjunction with the closed equation of its kinematic chain. The result is an equation of static moments of moving link masses containing single linearly independent vectors. They follow the conditions for balancing the mechanism by reducing the coefficients to zero which are time-dependent. This method found further development and applications in works (Bagci 1979; Balasubramanian and Bagci 1978; Berkof et al. 1977; Elliot and Tesar 1982; Smith 1975; Tepper and Lowen 1972a; Walker and Oldham 1978; Yao and Smith 1993).

Particularly, in (Smith 1975), an interactive computer program is developed which allows the design of fully force balanced four-bar linkages by the method of "linearly independent vectors". The increase in the shaking moment of these linkages is controlled by designing the counterweight such that the total moment of inertia of the associated links is made as small as possible.

2.1.2 Shaking Moment Balancing of Linkages

In the 1970's, great attention was given to the development of dynamic balancing methods. The principal schemes for complete shaking force and shaking moment balancing of four-bar linkages are presented in Fig. 2.2. In Berkof's approach (Berkof 1973; Fig. 2.2a), the mass of the connecting coupler 3 is substituted dynamically by concentrated masses located at joints B and C. Thus, the dynamic model of the coupler represents a weightless link with two concentrated masses. This allows for the transformation of the problem of four-bar linkage dynamic balancing (shaking force and shaking moment) into a problem of balancing rotating links carrying concentrated masses.

The parallelogram structure (Fig. 2.2b) has also been applied for complete shaking force and shaking moment balancing of four-bar linkages (Arakelian et al. 1992; Bagci 1982).

Ye and Smith (Ye and Smith 1991), Arakelian and Smith (Arakelian and Smith 1999), Gao (Gao 1989, 1990, 1991) and Berestov (Berestov 1975, 1977a; Fig. 2.2c, d) have proposed methods for complete shaking force and shaking moment balancing by counterweights with planetary gear trains. Esat and Bahai (Esat and Bahai 1999; Fig. 2.2e) used a toothed-belt transmission to rotate counterweights 5 and 6 intended for shaking force balancing which also allowed shaking moment balancing.

Another approach applied by Kochev (Kochev 1992a; Fig. 2.2f) was to balance the shaking moment (in the force balanced mechanism) by a prescribed input speed

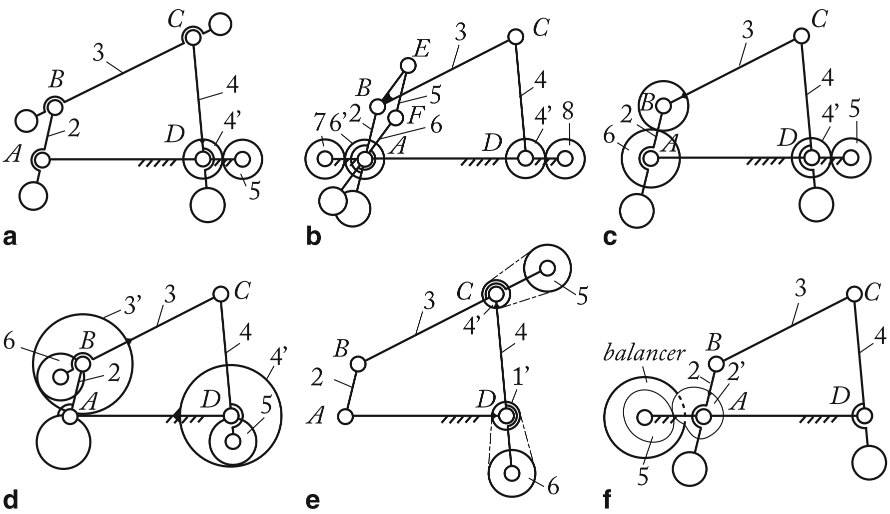

Fig. 2.2 Principal schemes for complete shaking force and shaking moment balancing of four-bar linkages with constant input speed

fluctuation achieved by non-circular gears or by a microprocessor speed-controlled motor.

In practice, all the known methods for complete shaking force and shaking moment balancing of four-bar linkages face serious technical problems. The schemes presented in Fig. 2.2a–d have a common disadvantage which is the connection of gears to the rocker. The resulting oscillations of the rocker create considerable noise unless expensive anti-backlash gears are used. Thus, in high-speed systems it is inadvisable to use gears connected to oscillating links. In the solution presented in Fig. 2.2e, this problem is solved partially by the use of toothed-belt transmission but the oscillations still cause serious technical problems. The method of non-circular gears balancing (Fig. 2.2f) always presents great engineering difficulty requiring the development of a special type of driver-generators.

Moore, Schicho and Gosselin have proposed all possible sets of design parameters for which a planar four-bar linkage is dynamically balanced without counter-rotations (Moore et al. 2009). This approach has been used in (Briot and Arakelian 2012) for the complete shaking force and shaking moment balancing of any four-bar linkage.

Figure 2.3 shows the schemes of complete shaking force and shaking moment balancing of four-bar linkages via copying properties of pantograph systems formed by gears (Arakelian and Dahan 2002; Arakelian and Smith 2005c). They will be further detailed in Chaps. 4 and 5.

Dresig and Nguyen proposed the shaking force and shaking moment balancing of mechanisms using a single rigid body called “balancing body” (Dresig and Nguyen 2011). By motion control of the balancing body, any resultant inertia forces and moments of several mechanisms can be fully compensated. The desired motion of

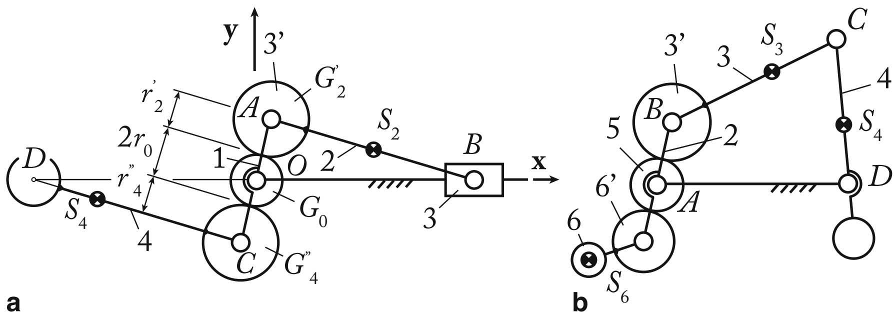

Fig. 2.3 Complete shaking force and shaking moment balancing of four-bar linkages based on the copying properties of pantograph systems

the balancing body is calculated in order that the sum of inertia forces and moments of the mechanisms and the balancing body will be zero.

However, it is evident that the complete dynamic balancing of mechanisms can only be reached by a considerably complicated design of the initial mechanism and by an unavoidable increase of the total mass. This is the reason why methods of partial dynamic balancing of mechanisms underwent a further development.

In the works (Berkof and Lowen 1971; Carson and Stephens 1978; Freudenstein 1973; Jacobi 1969; Lowen and Berkof 1970, 1971; Sconfeld 1974; Tricamo and Lowen 1983a, b), different modes of minimization of the shaking moment are suggested and are of interest. F. Freudenstein, J. P. Macey, E. R. Maki (Freudenstein et al. 1981) derive the equations for minimizing any order of combined pitching and yawing moments by counterweighting the driveshaft or a shaft geared to the driveshaft. The equations are given directly as a function of the harmonic coefficients of pitch and yaw and apply to any plane machine configuration. J. L. Wiederrich and B. Roth (Wiederrich and Roth 1976) proposed simple and general conditions for determination of the inertial properties of a four-bar linkage that allow partial momentum balancing. Dresig et al. (Dresig et al. 1994; Dresig and Schönfeld 1971, 1976a, b; Dresig and Jacobi 1974) examined the optimum balancing conditions for various structural forms of planar six and eight-bar linkages. A least-square theory for the optimization of the shaking moment of fully force-balanced inline four-bar linkages, running at constant input angular velocity, is developed in the studies of J. L. Elliot and D. Tesar (Elliot and Tesar 1977) and (Haines 1981).

V. A. Shchepetilnikov (Shchepetilnikov 1968, 1982) suggested the minimization of the unbalance of shaking moment by transferring the rotation axis of the counterweight mounted on the input crank. In his works, the first harmonic of the shaking moment is eliminated by attaching the required input link counterweight, not to the input shaft itself, but to a suitable offset one which rotates with the same angular velocity. This approach is original in that, while maintaining the shaking force balance of the mechanism, it is possible to create an additional balancing moment, reducing thereby the shaking moment. This approach has been developed in (Arakelian and Dahan 2000 a, b, 2001a, b; Arakelian and Smith 2004).

The particularities of the studies (Tepper and Lowen 1973; Urba 1981) resides in that a method is suggested permitting the comparison of the efficiency of balancing methods by the criterion of the minimum value of the shaking moment. F. R. Tepper and G. G. Lowen (Tepper and Lowen 1973) showed that in shaking force balanced mechanisms, the root-mean-square value of the principal inertia moment is constant relative to some ellipses located in the mechanism plane. By decreasing the dimensions of the ellipses, the root-mean-square value decreases and reaches a global minimum in the centre of this family of ellipses. This theory of isomomental ellipses was developed by A. L. Urba (Urba 1981) for the case of three-dimensional mechanisms. It was shown that the ellipses are transformed into ellipsoids and the properties mentioned are maintained.

Optimization algorithms based on programming are also widely used in balancing theory. The following studies are of interest: the studies of J. P. Sadler et al. (Conte et al. 1975; Porter and Sandler 1973; Sadler and Mayne 1973; Sadler 1975), H. Dresig and S. Schönfeld (Dresig and Schönfeld 1976 a, b), P. Jacobi (Jacobi 1972), J. M. O'Leary and G. W. Gatecliff (O'Leary and Gatecliff 1989), N. M. Qi and E. Pennestri (Qi and Pennestri 1991), M. J. Walker and R. S. Haines (Walker and Haines 1982a), as well as the studies (Demeulenaere et al. 2004b; Lee and Cheng 1984; Smith and Walker 1976; Smith et al. 1977a, b; Tepper and Lowen 1972b; Yan and Soong 2001). Among the recent studies based on various optimization techniques, it should be noted (Chaudhary and Saha 2007, 2008a, b, 2009; Chiou et al. 1998; Demeulenaere 2004; Demeulenaere et al. 2004a, b, 2006, 2008; Emdadi et al. 2013; Erkaya 2013; Ettefagh et al. 2011; Farmani and Jaamiolahmadi 2009; Ilia and Sinatra 2009; Li and Tso 2006; Verschuure et al. 2007, 2008a; Yan and Soong 2001).

M. A. K. Zobairi, S. S. Rao and B. Sahay (Rao 1977; Zobairi et al. 1986a, b) studied the problems of balancing taking into consideration the elasticity of links. The acceleration field resulting from the vibration of the links develops additional inertia forces called kineto-elastodynamic inertia forces. These works take into account the contribution of the kineto-elastodynamic inertia forces towards the shaking force and shaking moment while balancing planar mechanisms. Combining kinematic design and dynamic stress considerations, an optimal kinematic design of the mechanism satisfying the given aim and optimal cross-sectional areas of the links were determined such that the shaking force transmitted to the foundations due to the combined effect of rigid-body inertia forces and kineto-elastodynamic inertia forces is a minimum. The effect of the inclusion of kineto-elastodynamic inertia forces has been demonstrated by taking an example problem in which the maximum shaking force produced during the complete cycle of motion of mechanism has been minimized using nonlinear programming techniques.

The elastic behavior of a counterweighted four-bar linkage was first investigated theoretically and experimentally by Jandrasits and Lowen (Jandrasits and Lowen 1979a, b). The effect of link shape on the dynamic response of flexible mechanisms has also been studied (Yu and Smith 1995). The shaking force and shaking moment balancing of flexible mechanisms using redundant drives has been investigated theoretically and experimentally in (Yu and Jiang 2007). Experimental study on the elastodynamic behavior of the unbalanced and the counterweighted four-bar mechanisms has been considered in (Raghu and Balasubramonian 1990). The dynamic operation of a four-bar linkage, taking into account elastodynamic aspects, has also been studied in (Martini et al. 2013).

A novel method has been developed in (Lin 2000; Yu and Lin 2003) for the shaking force and shaking moment balancing of flexible mechanisms. The theoretical analysis and numerical results of a flexible four-bar linkage illustrated that the redundant actuators are useful for the optimum balancing of flexible linkages.

A. P. Bessonov (Bessonov 1967, 1968), for the first time, formulated and solved the balancing problem of mechanisms with variable masses of links. To obtain the optimal balancing of such mechanisms, he successfully applied the root-mean-square and mini-max methods of minimization.

The studies (Jacobi and Rose 1972; Offt 1974; Walker and Haines 1982a) are noticeable from the point of view of the experimental study of balancing of mechanisms. P. Jacobi and W. Rose (Jacobi and Rose 1972) conducted an experimental investigation of a theoretically fully force-balanced four-bar linkage. This study shows that the agreement between experimental and computed results was generally satisfactory. F. R. Tricamo and G. G. Lowen, in (Tricamo and Lowen 1981a, b) described a new concept for force balancing machines for four-bar linkages. On the base of the theoretical study, they proposed a device for the experimental application of this technique to a four-bar linkage. For the examined four-bar linkage the reduction of the shaking moment was more than 50 %.

Interesting results are also available in the field of balancing of spatial mechanisms. One of the first, M. V. Semenov (Semenov 1968a) was able to show that the kth harmonic of the shaking force for any spatial mechanism may be balanced by three counterweights disposed in mutually perpendicular planes. In (Gill and Freudenstein 1983a, b), computer-aided design procedures have been developed for the optimum mass distribution of the links of high-speed spherical four-bar linkages. R. E. Kaufman and G. N. Sandor (Kaufman and Sandor 1971) developed the method of linearly independent vectors for spatial mechanisms. The general approach is illustrated by the balancing of *RSSR* and *RSSP* spatial mechanisms. T. T. Gappoev developed the method (Gappoev and Tabouev 1979; Gappoev and Salamonov 1983) generalizing the Shchepetilnikov approach (Shchepetilnikov 1968, 1982) for the spatial version. He eliminated the first harmonic of the shaking moment by attaching the required input link counterweight, not to the input shaft proper, but to a suitably offset one which rotates with the same angular velocity. Balancing of the Bennett mechanism and *RCCC* spatial mechanism are studied in the works of N. Chen and Q. Zang (Chen and Zhang 1983; Chen 1984a, b). Y. Q. Yu (Yu 1987a, b, 1988) develops the method for balancing mechanisms by connecting additional dyads to the initial mechanism. The “method of static substitution of masses” has been used successfully in (Arakelian 2007) for complete shaking force and shaking moment balancing of *RSS’R* spatial linkage.

The studies of Wawrzecki (Wawrzecki 1998, 1999) relate to spatial mechanisms moving the needle of sewing machines. In the works of I. D. Belonovskaya, F. M. Dimentberg, L. B. Maysuk (Belonovskaya et al. 1987) the principles for building

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