Optimal dynamic balancing of planar mechanisms: An Overview

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The problem of dynamic balancing of planar mechanisms using the optimization technique is discussed in the paper. The application of different optimization algorithms in the process of dynamic balancing of three types of planar mechanisms: planar serial manipulator, four-bar linkage, and multi-bar mechanisms was analyzed. The aim of the paper is to provide an overview of recent research in optimal dynamic balancing of planar mechanisms. The author hopes that this study can be used as an informative reference for future research in balancing of mechanisms.

Keywords: Multi-objective optimization, Dynamic balancing, Planar mechanisms, Review

1. INTRODUCTION

During the operation of the mechanisms, inertial forces and moment occur, which are transmitted to the fixed joints and create dynamic loads. These dynamic loads have a negative impact on the functionality of the mechanism, i.e they cause the appearance of vibrations and noise, lead to inaccuracy of executive members, and affect the appearance of fatigue and friction. At the beginning of the last century, with the appearance of the first steam machine and internal combustion engine, this problem became evident and researchers faced the task of creating the theoretical bases for the mechanism balancing. In modern industry, which implies mass production and the use of mechanisms with high operating speeds, the mentioned negative impacts are unacceptable and their elimination is of crucial importance. In this sense, it is necessary to balance the mechanisms, that is partial or complete elimination of dynamic loads arising as a result of inertia. In other words, balancing of the mechanism implies the determination of such redistribution of moving masses of the mechanism that will provide small dynamic loads on the frame of the mechanism. The goal of balancing is to reduce vibrations, as well as to achieve better dynamics, reliability, and accuracy of the mechanism.

In general, there are two ways of balancing the mechanism: static balancing and dynamic balancing. Static balancing means the balancing of forces that are the result of inertia (shaking forces) and that appear in the fixed joints of the mechanism. The condition for achieving static balance is that the sum of all forces during motion must be equal to zero. Hence, it is necessary to make the center of mass stationary. On the other hand, dynamic balancing implies the simultaneous balancing of shaking forces and shaking moment [1, 2]. To achieve dynamic balancing, the following two conditions must be satisfied: 1) the sum of all forces must be equal to zero, and 2) the sum of all moments must also be equal to zero. Therefore, static balancing is a broader term than dynamic balancing, i.e dynamic balancing is a subset of static balancing (Figure 1) [3].

In various engineering fields (robotic mechanisms used in space) the achievement of dynamic balancing is of key importance. Otherwise, if the above-mentioned balancing conditions are not satisfied, the capabilities of the mechanism are significantly reduced.

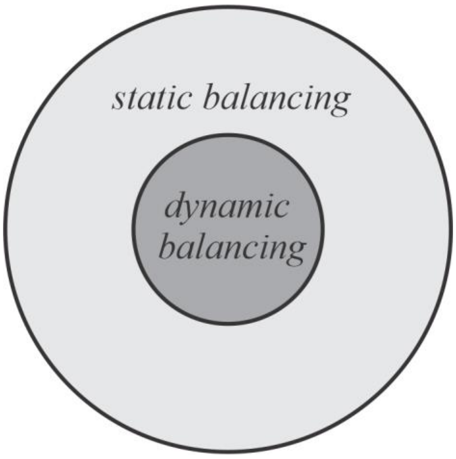

Figure 1: Static and dynamic balancing

Dynamic balancing of the mechanism can be achieved by using additional balancing components (counter-masses, counter-rotations, springs, and special four-bar linkages). The complete balancing of shaking forces and moment is a complex problem, so partial balancing techniques are most often used. Triciamo and Lowen [4,5] presented partial balancing techniques based on counterweights, which minimize the joint reaction forces, the driving torque, and the shaking moment, while the shaking forces have a maximum value. However, the application of additional balancing components in the dynamic balancing procedure increases the mass and inertia of the mechanism. These mechanisms are robust and require a higher consumption of materials and energy, and a larger space for accommodation, which is usually not acceptable from an economic aspect.

In order to avoid this, optimization techniques are increasingly applied for the purpose of dynamic balancing. In the paper below, a review of previous research, and a discussion of various optimization methods applied to achieve a dynamic balancing of different types of planar mechanisms are given.

The problem of balancing mechanisms is actual and very interesting to researchers. There are several laboratories in the world dealing with this problem and new results are published regularly. Mechanism balancing theory continues to be developed and new approaches and solutions are constantly being reported. The actuality of the balancing problem is also indicated by the fact that numerous studies have been conducted that reveal the

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specifics of the balancing theory. A detailed overview of the research and development of the methods in this field can be found in [6].

The rest of the paper is organized as follows: In Section 2, multi-objective optimization methods for dynamic balancing of mechanisms are presented. Section 3 provides an overview of the methods of optimal balancing of the planar serial manipulator, while Section 4 presents previous research in the dynamic balancing of four-bar linkage using optimization algorithms. The application of optimization techniques in the balancing of multi-bar planar mechanisms is presented in Section 5. Finally, in Section 6, conclusions and directions for future research are provided.

2. FORMULATION OF THE OPTIMIZATION PROBLEM AND APPLICATION OF THE MULTI-OBJECTIVE OPTIMIZATION IN THE DYNAMIC BALANCING OF PLANAR MECHANISMS

Since the goal of dynamic balancing is the minimization (elimination) of the joint reaction forces shaking forces and shaking moment, the problem can be defined as follows:

$$\min\left(F_1\left(\mathbf{X}\right),F_2\left(\mathbf{X}\right),...,F_n\left(\mathbf{X}\right)\right) \quad (1)$$

on condition:

$$g_j(\mathbf{X})\leq 0,\quad j=1,...,m \quad (2)$$

where $F_i\left(\mathbf{X}\right)\left(i=2,...,n\right)$ are objective functions, $g_j(\mathbf{X})$ are constraints of functions, and m is a number of constraints. $\mathbf{X}=\left\{x_1,x_2,...,x_D\right\}$ is a vector of design variables, and D denotes the number of design variables.

Based on the above, the dynamic balancing of planar mechanisms implies the simultaneous optimization of two or more objective functions i.e the considered problem can be solved using multi-objective optimization (MOO). In general, MOO is applied in all areas when one has to make a decision that implies a compromise between two or more conflicting objectives. Unlike single-objective optimization, in MOO there is no unique solution that simultaneously optimizes each of the defined objective functions. Therefore, in the case of MOO, the objective functions are contradictory and there are a greater number of optimal solutions.

In the literature, two methods are most often used to solve MOO problems:

1. the method of weighting factors
2. the method of *Pareto* front

The method of weighting factors implies the use of weighting coefficients (factors) in order to linearize the problem, i.e to form a unique objective function. This reduces the multi-objective optimization problem to a single-objective optimization problem. In the *Pareto* front method, linearization of the problem is achieved by using the best values for each of the objective functions. These values are equivalent to the weighting factors and enable the transformation of multi-objective into single-objective optimization.

3. OPTIMAL DYNAMIC BALANCING OF PLANAR SERIAL MANIPULATOR

Due to its simplicity and wide representation in various areas of industry, this type of manipulator is very interesting to researchers and has been often discussed in the literature.

The minimization of torques in the joints of a 2-DOF serial manipulator (Figure 2) using the method of optimal mass redistribution of the links was analyzed in [7, 8]. Each link of the planar manipulator is represented by an equivalent system of three point masses. For such an equivalent system, the equations of motion were determined, and then the problem of minimizing the torques in the joints was solved using MOO. The method of weighting factors was used in MOO procedure, and the objective function was defined as follows:

$$\text{Minimize } F(\mathbf{X})=w_1\tau_1+w_2\tau_2 \quad (3)$$

where w_1 and w_2 are weighting factors, and τ_1,τ_2 denote torques in the joints of the manipulator.

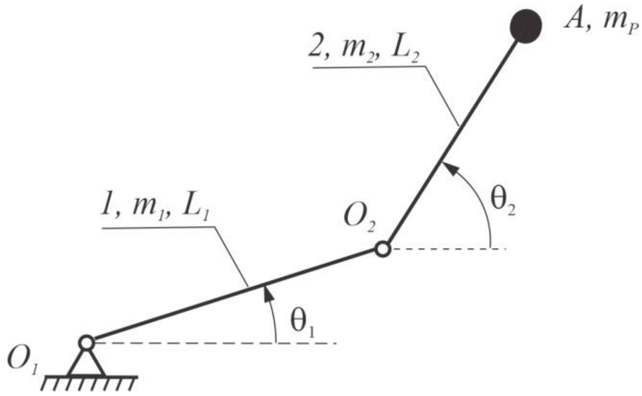

Figure 2: Serial manipulator

The same optimization problem was considered by Arakelian et al. [9] and they applied the method of adding counterweights to solve it [10, 11]. Harl, Oblak and Butinar [12] considered the problem of minimizing joint reaction forces in a serial manipulator. The problem of minimization of these quantities was solved by an adequate choice of the length of the manipulator links and the application of weighting factors in the MOO procedure. A comparison of the effectiveness of two methods used for balancing the dynamic joint reaction forces of a planar manipulator was presented by Šalinić et al. [13]. In the first method, the balancing of the joint reaction forces is achieved by applying interpolation polynomials [14], while in the second method, the same goal is achieved by adding counterweights to the manipulator links. By using the Lagrange's equations with multipliers [15], applying velocity transformation methods and representing the manipulator links with an equivalent system of point-masses, it is possible to calculate the dynamic joint reaction forces. To solve the MOO problem (minimization of two objective functions that determine the joint reaction forces), the differential evolution algorithm was applied. The objective function was defined as follows:

$$F=\frac{w_1}{\delta}\sqrt{\sum_{i=0}^{\delta}f_1^2\left(t_i\right)}+\frac{w_2}{\delta}\sqrt{\sum_{i=0}^{\delta}f_2^2\left(t_i\right)} \quad (4)$$

where w_1 and w_2 are weighting factors which values are $w_1=w_2=0.5$. The quantities under the root determine the resultant forces in the joints of the manipulator.

It should be emphasized that the application of optimization techniques in all analyzed studies of dynamic balancing of the planar serial manipulator gives satisfactory results, i.e it leads to a significant reduction in the values of the considered dynamic quantities.

4. OPTIMAL DYNAMIC BALANCING OF FOUR-BAR LINKAGE

Four-bar linkages (Figure 3) are widely used in mechanical devices (especially in rotary engines) owing to their simplicity, ease of manufacturing, and low cost. These mechanisms are usually applied for achieving a special motion duty like path generation. However, they operate at high speeds in the industry and it causes an unbalancing problem. In the text below, the problem of dynamic balancing of this type of planar mechanisms will be considered using the optimization procedure.

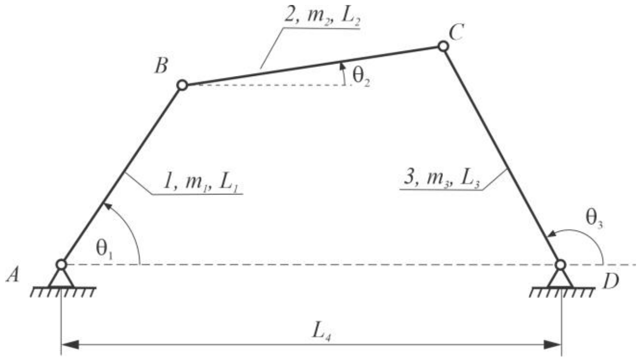

Figure 3: Four-bar linkage

K. Chaudhary and H. Chaudhary [16] presented an optimization technique that achieves dynamic balancing of the four-bar linkage based on the redistribution of the mass of the links. Namely, the minimization of shaking forces and moment was carried out using the genetic algorithm (GA). The problem of minimizing these dynamic quantities is solved as a MOO problem. In the first case, the weighting factors are used to solve the MOO problem, reducing the problem to a single-objective one. The objective function was defined as follows:

$$\text{Minimize } F(\mathbf{X}) = w_1 f_{sh} + w_2 n_{sh} \tag{5}$$

where w_1 and w_2 are weighting factors, f_{sh} denotes shaking force, and n_{sh} indicates shaking moment. In the second case, the *Pareto* front was applied to solve the MOO problem. The results obtained using both methods show a significant reduction in the value of dynamic loads.

The same problem was analyzed by Erkaya [17]. The problem of balancing of the four-bar linkage is formulated as an optimization problem and was solved by applying a Genetic Algorithm (GA). The MOO problem (minimization of shaking force and shaking moment) was solved by using weighting factors. Three cases, in which the values of these factors vary, were analyzed. It has been shown that an adequate choice of weighting factors and the structure of the objective function play a significant role in obtaining optimal values of design variables.

Bošković et al. [18] solved the problem of dynamic balancing of the four-bar linkage by applying a new algorithm called the Sub-Population Firefly Algorithm (SP-FA). The proposed algorithm is a modified (improved) version of the standard Firefly Algorithm (FA). By applying the SP-FA algorithm, the simultaneous minimization of eight objective functions was performed, which include joint reaction forces, driving torque, shaking forces, and shaking moment. By applying the proposed algorithm, the use of weighting factors was avoided and a significant reduction in the values of shaking force and moment was achieved (Figure 4). Also, the values of joint reaction forces are significantly smaller compared to the original (Figure 5). Thus, the efficiency of the proposed algorithm was proven.

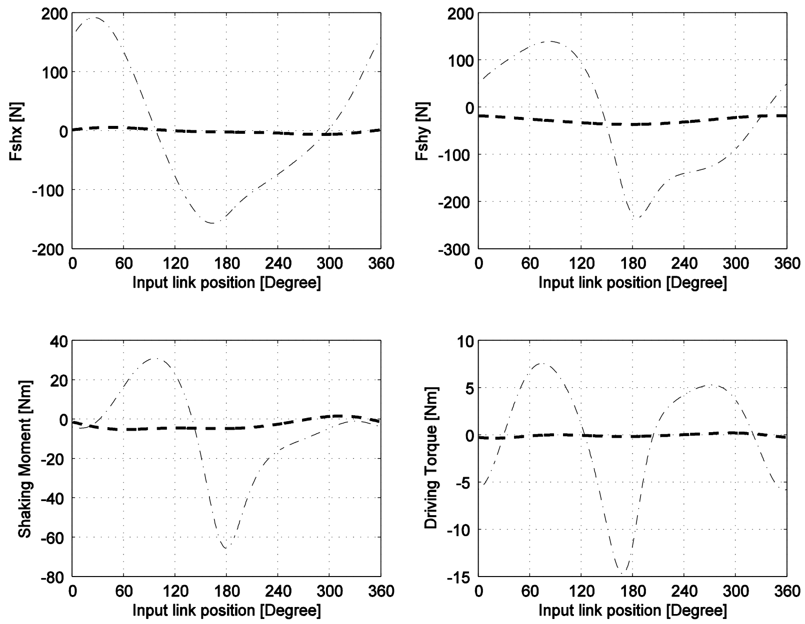

Figure 4: Original and optimized values of shaking forces, shaking moment and driving torque [18]

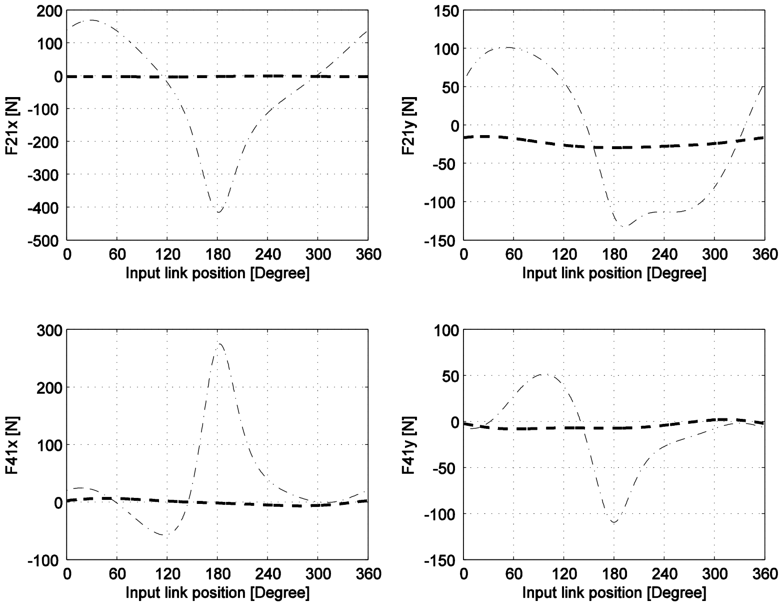

Figure 5: Original and optimized values of ground joint reaction forces [18]

Based on research and results obtained in [17, 18], Bošković et al. [19] developed a new algorithm called the Hybrid Cuckoo Search and Firefly Algorithm (H-CS-FA) and applied it to solve the problem of dynamic balancing of the four-bar linkage. Authors analyzed three cases where the simultaneous minimization of eight, nine and three objective functions is performed. The obtained results were compared with the results obtained by applying the basic algorithms (CS and FA), thus proving the effectiveness of the proposed H-CS-FA.

Percentage decrease of values of dinamic quantities obtained in [17, 18, 19] is shown in Table 1. It is obvious that the application of proposed optimization algorithms in the dynamic balancing procedure gives excellent results.

Table 1: Comparative view Percentage decrease of values of dinamic quantities

	Erkaya [17] (Case 1)	Erkaya [17] (Case 2)	Erkaya [17] (Case 3)	Bošković [19] (Case 1)	Bošković [19] (Case 2)	Bošković [19] (Case 3)	SP-FA [18]
F21x	95.52	88.04	93.50	97.83	90.293	90.92	99.26
F21y	77.18	31.66	59.10	71.33	69.22	75.65	71.88
F41x	84.69	51.48	78.28	80.63	84.64	76.03	92.91
F41y	74.95	21.59	56.58	53.90	72.67	77.69	85.12
Fshx	90.96	69.35	86.30	90.38	79.06	99.19	96.78
Fshy	77.54	37.61	61.54	71.95	69.70	77.40	75.85
Msh	76.21	25.51	58.73	51.63	69.34	76.38	83.39
M1	73.46	57.65	70.49	90.32	92.55	94.76	97.54

In the latest research, Etesami et al. [20] proved that the problem of dynamic balancing of the four-bar linkage is essential for its greater efficiency. A multi-objective Differential Evolution algorithm is used for *Pareto* optimization balancing of a four-bar linkage while considering the shaking moment and horizontal and vertical shaking forces as objective functions. The Pareto charts of five-objective optimization show a large number of non-dominated points, which provide more choices for optimal balancing design of the planar four-bar mechanism. A comparison of the results obtained from this study with those reported in the literature shows a significant decrease in shaking forces and shaking moment.

5. OPTIMAL DYNAMIC BALANCING OF MULTI-BAR MECHANISMS

In the last two decades, five-bar planar mechanisms (Figure 6) have been extensively used in various industrial fields, especially in robotic applications for mass production such as assembly, transportation, and positioning, as well as haptic and medical devices. There are a variety of five-bar planar manipulators depending on whether the actuators are rotary or linear [21].

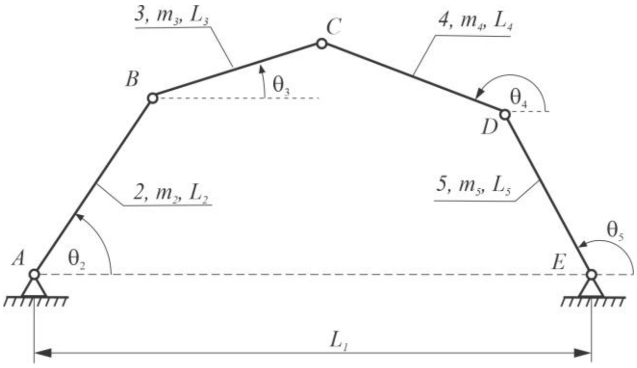

Figure 6: Five-bar mechanism

D. Kavala Sen et al. [21] analyzed the problem of dynamic balancing of five-bar planar manipulator for the largest trajectory in a usable workspace. The minimization of shaking forces and shaking moment was considered as an optimization problem which was solved by application of three different population-based optimization techniques: Particle Swarm Optimization, Genetic Algorithm, and Differential Evolution. The results show that an adequate selection of weighting factors and appropriate optimization algorithm allows achieving a significant reduction in the values of shaking force and moment.

Six bar mechanism (Figure 7) is a one degree of freedom mechanism which is constructed from six links. Klann linkage used to drive the legs of a walking machine. Six-bar mechanism is used in Watt mechanism, Stephenson mechanism, missile launcher and bellow valves etc [22].

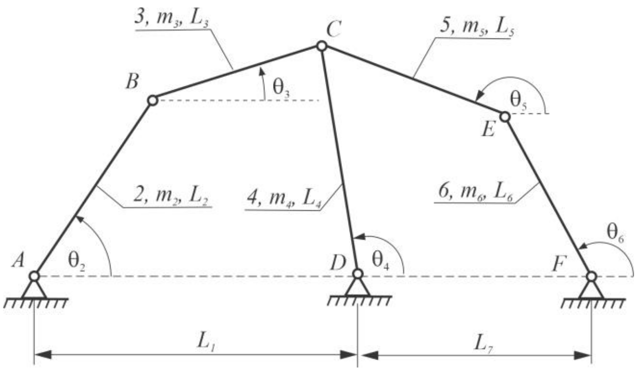

Figure 7: Six-bar mechanism

Belleri and Kerur [22] analyzed the problem of optimal dynamic balancing of the planar six-bar mechanism. The goal is to eliminate or minimize shaking force and shaking moment by applying genetic algorithm (GA). Two cases, with differently defined values of the weighting factors, were considered. It has been shown that the selection of weighting factors has a crucial role to obtain the optimum values of design parameters. The obtained values of shaking force and shaking moment are significantly reduced compared to the original values.

A further step in the investigation of the balancing problem of the six-bar mechanism was made in [23]. By adding counterweights, dynamic balancing of the considered mechanism was performed. The problem of minimization of the shaking force and the shaking moment was considered as a MOO problem and was solved using the Differential Evolution (DE) algorithm. The *Pareto* front is used to determine the best solutions according to three optimization criteria: only the shaking force, only the shaking moment, and both the shaking force and shaking moment. Numerical results show that the values of dynamic quantities are significantly reduced in relation to the original.

6. CONCLUSION

The theory of balancing mechanisms continues to develop and papers about new solutions in this area are constantly appearing. Special attention is paid to balancing methods based on the application of optimization algorithms. The continuous development and the appearance of new biologically inspired algorithms create the basis for further research in the field of optimal balancing. At the moment, it is difficult to say which is the best approach in multi-objective optimization of planar mechanisms. Depending on the chosen optimization algorithm and the user's requirements, one multi-objective optimal balancing method can be chosen over the other.

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