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Investigation on Inertia Force Balancing and Torque Compensation of Slider-Crank Mechanisms

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Abstract

This paper proposes a new design concept, which allows the simultaneous inertia force balancing and input torque compensation in slider-crank mechanisms. In the previous study, the inertia forces have been cancelled via a cam mechanism carrying a counterweight. Then, the spring designed for maintaining contact in this balancing cam mechanism has been used for torque compensation. Therefore, the spring has been jointed with a second cam mounted on the input crank. Thus, a complete balancing has been achieved. The present study proposes to minimize the shaking force and the input torque by a single cam. The proposed design concept allows one to use only one cam for solving the both mentioned problems. The suggested solution is illustrated by CAD simulations, which show its efficiency.

Keywords: Balancing, Inertia forces, Input torque, Crank-slider mechanism, Multi-criteria optimization, Cam mechanism, Motion law.

Introduction

Fast machines are subject to significant sources of varying dynamic loads. These variable dynamic loads cause the problems of vibration and fluctuation of the input torque. These two problems are well known and many methods have been developed and documented [1-3]. To minimize or cancel vibrations of frame structures, the inertia forces and moments balancing is applied V Arakelian [4]. The input torque may be reduced by optimal redistribution of moving masses [5-10]or by using non-circular gears [11]. Demeulenaere [12]proposed a wide variety of input torque balancers, mainly based on inverted cam mechanisms and on a centrifugal pendulum guided by a fixed cam [6,13].Divers "kinetic balancers" have been proposed in [14] the balancer consists in a flywheel driven through a noncircular gear pair. In Jing [15] a simple differential gear train is used as active balancer in order to connect directly the input shaft to the follower. One of the more efficient methods used to solve the problem of input torque balancing is creating a cam-spring mechanism, in which the spring is used to absorb the energy from the system when the torque is low, and release energy to the system when the required torque is high. It allows reducing the fluctuation of the periodic torque in the high-speed mechanical systems [16-23].

These themes are examined separately, as two decoupled problems. However, they can be considered together, since these problems are solved through the optimal redistribution of energy in mechanical systems.

In V. Arakelian [24] it was proposed to combine the mentioned problems and to balance inertia forces and the input torque simultaneously by two separate cams connected with a counterweight and a spring (Figure 1). The counterweight (6) ensures the inertia force balancing of the mechanism and the spring (8) ensures permanent contact between the rollers and the cams, as well as the balancing of the input torque. The conditions of such a simultaneous balancing have been discussed and validated via CAD simulations.

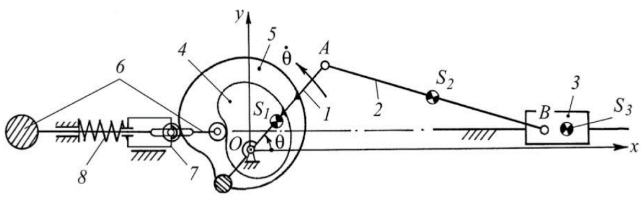

Figure 1: Slider-crank mechanism balanced by means of two cams: 4 and 5.

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The present study proposes a new solution to simultaneously compensate the inertial forces and the input torque in slider-crank mechanisms via a single cam combined with a counterweight and a spring (Figure 2). In other words, the cams (4) and (5) are replaced by a single cam (4 in Figure 2), which ensures both the displacement of the counterweight (6) for balancing the inertia forces and the displacement of the compression of spring (8) of input moment balancing.

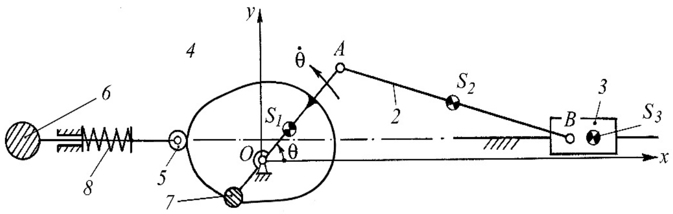

Figure 2: Slider-crank mechanism balanced by means of a cam

It is obvious that the simultaneous balancing carried out according to the scheme shown in Figure 2 will not be perfect. In this case, partial compensation of the inertia forces and the input torque will be accomplished.

Problem formulation

In order to better understand the problem that will be considered in the paper, let us first deal with the solution proposed in V. Arakelian [24]. The slider-crank mechanism examined in previous work uses two cams to be able to compensate the inertia forces and the input torque. By thus decoupling the laws of motion to generate the optimal inertia and elastic forces, it was found analytically the solution to simultaneously compensate the inertia forces and torque input.

The cam 4 (Figure 1) permitting the mechanism to compensate the alternative inertial forces has a motion law imposed by the relationship:

$$\ddot{x}_{s6} = -\frac{m_b + m_3}{m_6}\ddot{x}_B \qquad (1)$$

where, m_3 is the mass of the slider, m_B is the mass of the rod2 substituted to the axis of the slider, m_6 is the mass of the follower with counterweight, $\ddot{x}_{s6}$ is the acceleration of the follower and is the acceleration of the slider.

The profile of the cam 5 for compensation of the input torque is determined from the following relationship:

$$\tau = \left(m_b + m_3\right)\left(1 + \frac{m_b + m_3}{m_6}\right)\left(\frac{\partial x_b}{\partial \theta}\right)\left(\frac{\partial^2 x_b}{\partial \theta^2}\right)\omega^2 + k\frac{\partial \delta}{\partial \theta} \qquad (2)$$

where, x_b is the displacement of the slider 3, θ is the rotation angle of the crank 1, $\omega = \dot{\theta}$ is the angular velocity of the crank 1, k is the stiffness of the spring 8, δ is the displacement of the end of the spring with respect to its equilibrium position.

To compensate the input torque of the mechanism, the law of motion of δ must therefore be generated in such a way that $\tau = 0$.

In the case of a mechanism with a single compensation cam, there are two equations depending on δ:

$$F = \ddot{x}_{s6} m_6 + (m_b + m_3)\frac{\partial^2 \delta}{\partial \theta^2}\omega^2 \qquad (3)$$

$$\tau = \left(m_b + m_3\right)\left(1 + \frac{m_b + m_3}{m_6}\right)\left(\frac{\partial x_b}{\partial \theta}\right)\left(\frac{\partial^2 x_b}{\partial \theta^2}\right)\omega^2 + k\frac{\partial \delta}{\partial \theta}\delta \qquad (4)$$

It can be seen that δ, as well as its first and second derivatives, are included in two different equations. Explicit resolution of these equations is not considered in this study. A method for numerically solving this problem is discussed. Thus, the purpose of the suggested balancing with a single cam is to minimize the inertia forces of the mechanism, as well as the input torque.

Therefore, two criteria for minimization are introduced:

$$C_1 = \sum_{\theta=0}^{2\pi}\left|\tau\right| \qquad (5)$$

$$C_2 = \sum_{\theta=0}^{2\pi}\left|F\right| \qquad (6)$$

An important constraint is the assured contact between the cam and the follower, which implies that the force generated by the spring must always be greater than or equal to that generated by alternative acceleration.

$$k\delta \geq \left(m_b + m_3\right)\ddot{x}_b$$

It is understood that the pressure angle must remain within the admissible limits.

Determination of the motion law

The law of motion δ will be so determined over the interval [0; 2π]. Thus, there are a number of points n in this interval with m boundary conditions. The law creation method follows that developed in L. Moussafir [25]. They therefore also define a connection class between each generated spline. The boundary conditions allow to modify the general shape of the splines created by polynomial interpolation. The different splines are then connected with the class defined upstream to form the complete motion law. The curve obtained is then discretized into a defined number of values. The dynamic equations (3) and (4) can be calculated as well as the criteria (5) and (6).

The optimization algorithm will therefore take care of modifying the boundary conditions in order to minimize the two criteria considered while ensuring compliance with the contact stress and the pressure angle. The problem being multi-objective, a large number of optimized solutions can be found. Pareto-optimal solutions have been used to restrict the choices. Please note that the final solution being at the decision of the designer.

Illustrative example

The following parameters will be used for the simulation: L_{OA} = 0.292 m, L_{AB} = 0.427 m, $r_1 = 0.5L_{OA}$; $r_2 = 0.5L_{AB}$, y_B = 0.1 m, m_1 = 2 kg, m_2 = 3 kg, m_3 = 4 kg, I_{S1} = 0.03 kg/m^2, I_{S2} = 0.14 kg/m^2, where, L_{OA} is the distance between axes O and A , L_{AB} is the distance between axes A and B, $r_1 = l_{OS1}$ is the disposition of the center of mass of the crank 1, $r_2 = l_{AS2}$ is the disposition of the center of mass of the rod 2, y_B is the offset of the slider 3, m_1 is the mass of the crank 1, m_2 is the mass of the rod 2, m_3 is the mass of the slider 3, I_{S1} is the axial inertia of the crank 1, I_{S2} is the axial inertia of the rod 2.

The period of time for a cycle of the mechanism is fixed at 1 sec. By choosing r_{cp}=0.2m, we obtain m_{cp}=3.25kg, where r_{cp} is the distance between the center of mass of the counterweight and the axis of rotation O, m_{cp} is the mass of the counterweight in order to balance the mass m_A due to the substitution of the mass m_2 of the rod 2 by two point masses [3] and the mass of the crank 1.

Thus, the motion law has 6 distinct points, due to the geometry of the cam, the first and the last point will have the same boundary conditions.

The considered problem is characterized by the following parameters: variables X=[$x_a,x_b,x_c,x_d,x_e,y_a,y_b,y_c,y_d,y_e,\dot{y}_a\dot{y}_b,\dot{y}_c,\dot{y}_d,\dot{y}_e,\ddot{y}_a,\ddot{y}_b,\ddot{y}_c,\ddot{y}_d,\ddot{y}_e,m_6,k$]; number of generation: 300 MOGA II, design of experiments: 20 SOBOL; number of goals: 2; minimize C_1, C_1; number of restrictions: $k\delta \geq (m_b + m_3)\ddot{x}_b$ and $\alpha \leq \alpha_{adm}$, where α is the pressure angle of the cam mechanism.

After optimizing the law of motion using the MOGA II algorithm, the following results were obtained (Figure 3 and Figure 4). Figure 5 shows the profile of an optimized cam. Thus, the numerical simulations show that a reduction of 30% of the maximum value of inertia forces and a reduction of 50% of the maximum value of the input moment have been achieved.

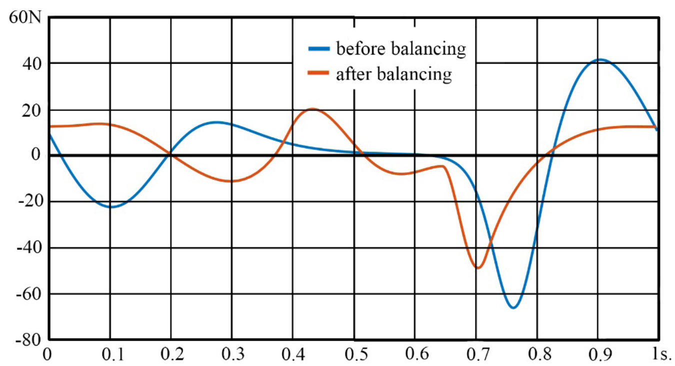

Figure 3: Inertial forces of the mechanism before and after balancing

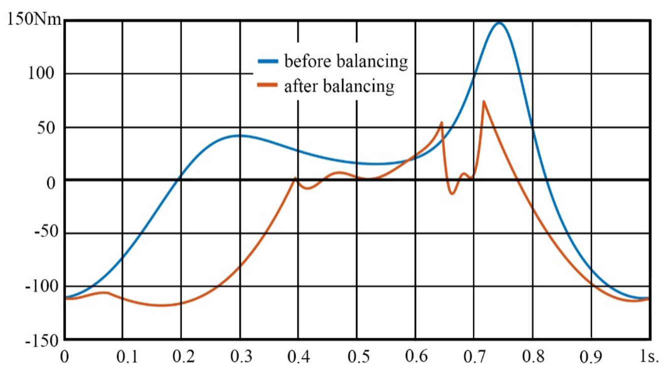

Figure 4: Input torque of the mechanism before and after balancing

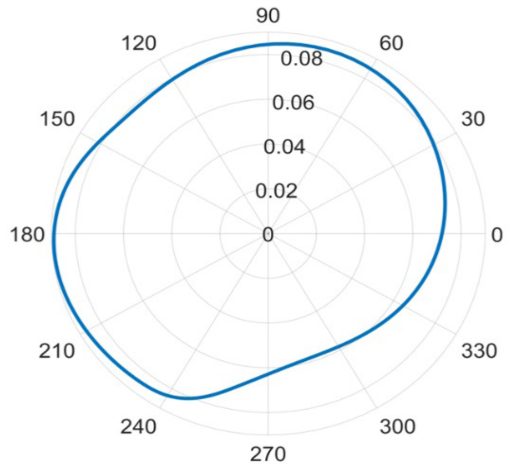

Figure 5: Cam profile ensuring simultaneous inertia force balancing and torque compensation

Conclusions

A continuous increase in the frequency of input speeds of various machines and devices is one of the features of modern technological progress. One of the main problems of the dynamics and design of high-speed machines is the minimization of the inertia forces that machines transmit to the environment through their frames. Another topic that is also very important in machine dynamics is minimizing the input torque caused by variable dynamic loads. Both of these problems are known, and many methods have been developed and documented. However, they are considered separately, as two unrelated issues. In the manufacture of machines, where the search for minimum cost is of principal importance, the method of simultaneously balancing the input torque and inertia forces by means of a single cam has a significant advantage. The method proposed in this paper shows how to solve such a problem. The given numerical example shows its efficiency.

References

1. Spinnler G. Conception des machines,Principeset applications. Presses polytechniquesetuniversitairesromandes. 2001; 2.

2. V Arakelian MS. Shaking force and shaking moment balancing of mechanisms: an historical review with new examples. Transactions of the ASME. Journal of Mechanical Design. 2005; 127(2):334-339.

3. V Arakelian SB. Balancing of linkages and robot manipulators. Advanced methods with illustrative examples. 2015.

4. Bruno Zappa VL. Design of Torque Balancing Mechanisms. Journal of Mechanics Engineering and Automation. 2017; 7:312-320.

5. Arakelian V. Complete shaking force and shaking moment balancing of RSS'R spatial linkages. Multi-body Dynamics Part K. 2007; 221:303–310.

6. Demeulenaere Ba. Improving Machine Dive Dynamics: A Structured Design Aproach toward Balancing. ASME J. mech. des. 2008; 130.

7. Berkof R. The input torque in linkages. In: Mechanism and Machine Theory; 1979. p. 61-73.

8. Chaudhary H. Balancing of four-bar linkages using maximum recursive dynamic algorithm. Mechanism and Machine Theory. 2007; 42:2016-2232.

9. Soong R. Minimization of the driving torque of full force balanced four-bar linkages. Journal of Kao Yuan Institute of Technology. 2001;591-594.

10. Yan HS. Kinematic and dynamic design of four-bar linkages by links counterweighing with variable input speed. Mechanism and Machine Theory. 2001; 36(9):1051–1071.

11. Yao YY. A new method for torque balancing of planar linkages using non-circular gears. Journal of Mechanical Engineering Science Part C. 2003; 217(5):495-503.

12. Demeulenaere B a. Input Torque Balancing Using an Inverted Cam Mechanism. Torque Balancing Using an Inverted Cam Mechanism. 2005; 887-900.

13. Demeulenaere BS. Experimental Validation of Input Torque Balancing Applied to Weaving Machinery. Journal of Mechanical Design. 2008; 130(2):1-10.

14. Dooner DB. Use of Noncircular Gears to Reduce Torque and Speed Fluctuations in Rotating Shafts. Journal of Mechanical Design. 1997; 119(2):299-306.

15. Jing SaA. An Active Gear Balancer for Torque Compensation. Journal of Mechanical Design. 2011; 133(1):1-10.

16. Angeles JWCJ. The optimum synthesis of en elastic torque-compensating cam mechanism. In: Mechanism and Machine Theory; 2001. Vol. 36.p. 245-259.

17. Arakawa MN. Torque compensation cam mechanism. Proceedings of Joint International Conference on Advanced Science and Technology; 1997. p. 302–305.

18. Benedict CM. Torque balancing of machines by sub-unit cam systems. Second Applied Mechanism Conference, (p. paper No. 15); 1971; Oklahoma State University, Stillwater, Oklahoma; 1971.

19. Benedict CT. Optimal torque balance for a complex stamping and indexing machine. Mechanisms Conference, (pp. Paper No. 70-Mech-82); 1970. Columbus, Ohio; 1970.

20. Funk WH. On the complete balancing of the inertia-caused input torque for plane mechanisms. Proceedings of the Design Engineering Technical Conference; 1996. Irvine, California; 1996.

21. Guilan TH. A new method of torque compensation for high speed indexing cam mechanisms. ASME Journal of Mechanical Design. 1999; 121:319-323.

22. Nishioka M. Design of torque compensation cam using measured torque distribution. Proceedings of the 10th World Congress on the Theory of Machines and Mechanisms; 1999 Oulu, Finland.p. 1471–1476.

23. Nishioka MY. Direct torque compensation cam mechanisms. Transactions of the Japan Society of Mechanical Engineers. 1995; 61(585):2020–2024.

24. V Arakelian SB. Simultaneous inertia force/moment balancing and torque compensation of slider-crank mechanisms. Mechanics Research Communications Mechanics Research Communications. 2010; 37(2):265-269.

25. L Moussafir VA. Multi-criteria design optimization of cam mechanisms combining different splines given by checkpoints. Proceedings of the 15th World Congress in Mechanism and Machine Science; Jun 30 –July 4 2019; Krakow, Poland; 2019.