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Research paper

Mathematical modeling and optimization of cam mechanism in delivery system of an offset press

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ABSTRACT

This paper presents a new method for cam profile design and optimization by integrating a single objective optimization procedure with a dynamic model of cam-follower mechanism in delivery system of an offset press. The proposed approach based on a new strategy mainly includes two parts, a single objective optimization procedure for the kinematic characteristics of the follower and a dynamic model for the cam-follower mechanism. For the first part, the follower acceleration profile is described by modified trapezoidal curve, thereby deriving the velocity, jerk and displacement functions, respectively. Then sequential quadratic programming (SQP), which deals well with equality and inequality constrains, is adopted as the single objective optimized algorithm in this part. In the second part, a two degrees of freedom lumped parameter model taking into account the torsional flexibility and damping of the grippers, the contact compliance at the cam/roller and grippers/block interfaces, is established to investigate the dynamic behavior of the force-closed cam-follower mechanism. In order to improve the kinematic and dynamic characteristics of cam-follower mechanism synthetically, an optimization cycle, known as iterative process, is introduced to implement the procedure of single objective optimization and dynamic simulation alternately. The example illustrated in this paper, sufficiently demonstrates the effectiveness of the new method. Ultimately, the proposed approach gives cam designers a useful tool to design and optimize the cam profile, so as to reduce residual vibration.

1. Introduction

Cam-follower mechanisms, required to run at a constant speed to specify the variety of output motion, are widely used in mechanical industry because of its precise motion, design simplicity and relatively low lifecycle cost [1–3]. In addition, one of the most attractive features of a cam-follower mechanism is that it can easily create intermittent motion in which the follower is held motionless during portions of its cycle [4]. Since the cam profile, applied in delivery system, known as multiple-dwell curve, controls the open-closed armature position by determining the time of opening and closing events. The geometric quantities of the cam profile such as the displacement, velocity, acceleration and jerk, have to reach the specified values at the precise moment. The application of cam-follower mechanism in delivery system makes the design of the cam profile essential to the overall performance of a high-speed offset press.

The optimization methods used in cam design and optimization mainly consist of the representation of the cam profile and the selection of the optimization algorithm. In fact, a number of conventional and developmental curves have been suggested to express

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a cam profile in cam design, for example the cycloidal curve, the modified sine curve, the modified trapezoidal curve, the polynomial curve and the B-spline [5–8]. Once the profile is generated with regard to some kind of curve mentioned above, the geometric features and kinematic characteristics will be checked for feasibility, meanwhile the process is repeated until a feasible design is achieved. To avoid cam wear and follower jump, a modified trapezoidal profile which was suitable for single-dwell cam-follower mechanism, was presented by Flocker [9] to allow cam designers to easily choose a value for the maximum forward or the maximum backward acceleration. A combination of method based on a universal Hermite cam displacement was suggested to minimize and restrict vibrations in high-speed cam-follower systems over a range of speeds by Jiang et al. [10], which could form a general design environment in optimization problem. Instead of sine acceleration curve, a fractional polynomial mod trap spline was investigated by Acharyya and Naskar [11] to minimize follower jerk and contact stress, and experimental analysis was done to validate the predicted peak values of acceleration and jerk. On the other hand, a lot of traditional and evolutionary optimization algorithms have been adopted by researchers for cam optimal design. For traditional optimization algorithms, the golden section method [12], Lagrange multipliers method [13] and Kriging method [14] were proposed in the optimal design of cam profile. In addition some scholars eagerly focused on Genetic Algorithm [15], Particle Swarm technique [16] and multiobjective optimization [17] to deal with optimization problem recently, known as evolutionary optimization algorithms. Mermelstein and Acar presented [18] a method of synthesising cam profiles based on the use of piecewise polynomials together with an redefined quadratic programming algorithm, in the end, a means to prove the validity of the results was explained. Based on Genetic Algorithm and fuzzy membership function, the classical splines of 6, 7 and 8 orders and the B-splines of 6 and 8 orders were taken for designing cam displacement function to minimize the acceleration and jerk of the follower [19]. As an essential research effort in developing a new cam drive engine, an evolutionary multiobjective optimization approach [20] was applied to investigate a complex cam shape optimization problem, and the optimization results showed that the overall engine performance was improved significantly by the evolutionary multiobjective optimization approach compared with the initial design.

In high-speed cam-follower mechanisms, the motion accuracy of cam profile is a key factory, because it affects the whole machine performance. Over the decades, several approaches [21–23] have been proposed to improve the dynamic behavior of cam-follower mechanism by reducing follower undesired vibrations. Qiu et al. [24] proposed a universal optimal approach to cam curve design, which included both the kinematical and dynamical models of indexing cam mechanisms. Gatti and Mundo [25] addressed a preliminary study on the control of follower vibration in cam-follower mechanism by implementing a four degrees of freedom dynamic model which took into account the important effects due to the torsional and translational flexibility and damping of the cam and camshaft. Due to the dynamic effects, clearances, manufacturing and assembly errors in form-closed cam mechanisms, the follower jump could occur, therefore, a three degrees of freedom dynamic model [26] was proposed and the Hertzian theory for general profiles was used to investigate the interference fit between the conjugate cam profiles and the follower train.

Cardona et al. [27] proposed a procedure which automatically guaranteed both continuity in the displacement function, designed with non-parametric Bézier curves, for generating constant-breadth cam profiles. Zhou et al. [28] proposed an innovative method for the design and analysis of a high-speed cam mechanism by using Fourier series, the numerical results show that the proposed method could reduce the vibration of the cam mechanism. A particular cam shape was found for maximizing the range of stiffness variability of a novel adjustable compliant actuator by Torrealba [29], using differential evolution.

Until now, there have been few published literatures that integrated a single objective optimization procedure with a two degrees of freedom dynamic model in a unified manner to improve the kinematic and dynamic characteristics of the cam-follower mechanism. However, the cam-follower mechanism with an improper positive and negative acceleration will lead to inaccurate motion and severe residual vibration which need to avoid. Therefore, developing a new method capable of dealing with those undesirable problems is worthwhile for cam design. The purpose of this paper is to propose a new method to improve the kinematic and dynamic characteristics of cam-follower mechanism by integrating a single objective optimization procedure with a dynamic model. In addition, the numerical results will be detailed in the following aspects: (i) the kinematic characteristics of follower, (ii) influence of vibration on follower displacement, velocity and acceleration, (iii) comparisons between the original and the optimization at high speed, and (iv) influence of the stiffness and damping on residual vibration.

2. Problem description

To describe the mathematical modeling and optimization problem, the CAD model of cam-follower mechanism in a delivery system of offset press is taken into consideration as illustrated in Fig. 1(a). Actually, the delivery system shown in Fig. 1(b) mainly consists of a cam, a certain number of followers (gripper bars), a guideway, two sprockets, a delivery platform and a frame.

As shown in Fig. 1(b), the cam is securely fixed to the frame with bolts, conversely, the follower (gripper bars) moves on the guideway at a constant speed. A typical work flow for the delivery system can be described as follows: The chain, installed in the guideway, is driven by sprocket, simultaneously the gripper bars called follower moves on the guideway in a clockwise direction to implement the task of paper receiving. As the gripper bars contacts the cam, the paper from printing color group is transferred to the former. Finally, the gripper bars carrying the paper keeps moving to a certain location, thus the paper can be transmitted to the delivery platform accurately.

The open-closed armature position of grippers is controlled by cam profile, thus the kinematic behavior of cam profile such as the displacement, velocity, acceleration and jerk, have to reach the specified values at the opening and closing events. However, the vibration of follower increases with an increase in speed, leading to inaccurate motion and severe impact. In addition, the traditional method used in cam design is a trial-and-error approach which requires running the simulation many times and hence the whole design process is mind boggling and time-consuming. Therefore, it is necessary to develop an optimal design approach to determine