Mechanism and Machine Theory 104 (2016) 118–129

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Design and analysis of high-speed cam mechanism using Fourier series

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ARTICLE INFO

Article history:
Received 22 December 2015
Received in revised form 16 May 2016
Accepted 18 May 2016
Available online 8 June 2016

Keywords:
High-speed mechanism
Fourier series
Kinematic characteristics
Jerk
Impact velocity

ABSTRACT

This study proposes an innovative and comprehensive method for the design and analysis of a high-speed cam mechanism. In the proposed method, the displacement function of the cam follower is described using Fourier series. The coefficients of the series are obtained by constraint equations during the cam rise period and the minimum principle of displacement error function (where, error function refers to the variance between actual displacement and ideal displacement of the cam follower during the dwell). The validity of the proposed design method is verified through a case study with focus on high-speed cam mechanism design. In the design case, kinematic characteristic analysis of this cam follower shows that the order of continuous derivative of displacement transfer function is higher, the characteristic value of its dynamic torque is smaller, and its jerk at the impact point is smaller than some common disc cam mechanisms. The results indicate that the proposed method can reduce the vibration of the cam mechanisms and its impact velocity is smaller than the existing design methods.

1. Introduction

In the development of high-precision and high-speed cam mechanism, its dynamic characteristics and rubbing have become a major concern of the researchers [1–4]. Hrones et al. [5] demonstrated that dynamic characteristics of the cam follower with constant acceleration were worst at high speed in terms of theoretical analysis, which was proved by Mitchell [6] with experiments. To improve the dynamic characteristics, Hiroshi [7] described the displacement function of the cam follower using the combined curve of correction sine, trapezoidal and constant velocity curve, and on this basis Peng et al. [8] optimized its kinematic characteristics. Therefore, this design method has been applied widely in mid-speed cam mechanism. Sun et al. [9] proposed an approach to design the cam profile combining typical curves in Pro/e. Different types of spline curves were applied in the design of the cam mechanisms, and these design methodologies have improved its kinematic capability [10–13].

The dynamic characteristics of the high-speed cam mechanism were studied by many researchers, and different dynamic parameters were minimized for optimizing the cam profile. Gao et al. [14] optimized the cam profile of the zoom system based on the least square method. Cam with three circular-arc profiles was designed by Hsieh [15], and its kinematic characteristics are then investigated numerically using an equivalent slider-crank representation. Hsieh [16] obtained an analytical description of the driving cam profile using the coordinate transformation and the conjugate surface theory. Moreover, Qiu [17] and Fabien [18] improved the dynamic characteristics of the cam mechanism by optimizing the residual vibration of the cam follower. Wiederrich [19] and Gutman [20] studied the dynamic and frequency of cams using finite trigonometric series, respectively. However, the detailed design method was not elaborated and the errors

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http://dx.doi.org/10.1016/j.mechmachtheory.2016.05.009
0094-114X/

Nomenclature

$S(\theta)$	displacement transfer function
ε_s	the displacement error function
ε_v	the velocity error function
ε_a	the acceleration error function
O	rotational center of cam
B_0	rotational center of roller
A_0	rotational center of oscillating follower
d	distance between point A_0 and O
l	length of oscillating follower
r	radius of roller
β_0	initial angle between the direction of oscillating follower and the center line A_0O
β	angular displacement of the follower
α	pressure angle
φ_i	the angle between the line A_iO with the normal profile on contact point
ω_1	cam angular velocity
P_{13}	instantaneous center between cam and oscillating follower
D	distance between point P_{13} and point B_i
J	dimensionless jerk
M	the balance torque of the cam mechanism
M_d	dynamic torque
δ	gap between roller and cam working surface
v_{imp}	impact velocity
J_{imp}	dimensionless impact jerk on crossing point
j_2	rotational inertia of the follower
m_{23}	the mass of the roller (2) and the oscillating follower (3)
r_c	the distance between the center of mass and rotation center of the follower
F	the external load of the follower

during dwell cannot be controlled in their papers. In addition,to calculate the number of terms of the trigonometric series is not mentioned. The cam profile synthesis method using spline curves was well used in the design of cam profiles because of its superior controllability [21–23]. However, when the higher order of derivative for displacement curve is required continuously, the order and term number in the spline curves increase. And more coefficients of the terms have to be determined, which causes the amount of calculation to be much larger.

The existing literature lacks a systematic method for the design and synthesis of high-speed cams using a Fourier series. Therefore, this research presents an innovative design approach to high-speed cam mechanism using a Fourier series and a synthetic analysis method for its dynamic characteristics. The proposed method comprises four major steps: (1) theoretical analysis of the design of a Fourier series cam mechanism; (2) development of the displacement transfer function for the cam profile; (3) verification of the effectiveness of this approach for designing a Fourier series cam; and (4) a comparative study on the dynamic characteristics of the Fourier series cam concerning other common disc cams.

2. Design method for a Fourier series cam

When the cam mechanisms perform a periodic motion, the displacement function of the cam follower (hereinafter referred to displacement transfer function) can be described by one periodic function $S(\theta)$ (where θ is the rotational angle of the cam). According to the sufficient condition of the Dirichlet theory, $S(\theta)$ can be expanded as a convergent Fourier series. Namely, the function $S(\theta)$ can be expressed as

$$S(\theta) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos(k\theta) + b_k \sin(k\theta)) \tag{1}$$

where

$$a_0 = \frac{1}{\pi} \int_0^{2\pi} S(\theta) \mathrm{d}\theta$$

$$a_k = \frac{1}{\pi} \int_0^{2\pi} S(\theta) \cos(k\theta) \mathrm{d}\theta$$