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Analysis and Simulation of Cam Follower Mechanism using Polynomial Cam Profile

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Abstract

The cam follower mechanism is versatile and almost any arbitrarily-specified motion can be achieved. The use of algebraic polynomials to specify the follower motion is a new choice for cam profiles. This class of motion function is highly versatile especially in high speed automobiles. In the present work, kinematic and dynamic analyses of cam follower mechanism with polynomial cam profiles are carried out. The kinematic analysis presents follower displacement, velocity, and acceleration driven by a cam rotating at a uniform angular velocity. Dynamic analysis presents static and inertial forces developed in the mechanism. A 2-3 polynomial cam profile shows discontinuous follower acceleration at the ends of the stroke making it unsuitable at higher speeds. A 3-4-5 polynomial cam profile has an extended control as it provides a zero acceleration at the end points and no control over the follower jerks at end points. The modelling and simulation of a cam follower mechanism is performed on SolidWorks and results are presented for various cam speeds. The simulation results show substantially lower values of follower velocity and acceleration for 3-4-5 polynomial cam profile; hence, it is versatile and most suitable at higher speeds without much modifications.

Keywords: *Cam Follower Mechanism, Kinematic Analysis, Dynamic Analysis, Polynomial Cam Profile, Simulation.*

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1. Introduction

In any class of machinery where automatic control and accurate timing are important, the cam is an indispensable part of mechanism. It is a curved outline or a curved groove, which, by its oscillation or rotation motion, gives a predetermined specified motion to the follower. Cam follower mechanisms find application in a wide variety of devices and machines, such as printing presses, shoe machinery, textile machinery, automobile engines and pumping devices. The application of algebraic polynomials for cams was developed by Dudley, in which the differential equations of motion are solved using polynomial follower motion equations. Stoddart [1] further showed an application of these polynomial equations to cam action. In polydyne cams, the profile is designed such that the follower lift curve matches a desired polynomial equation giving the cam follower mechanism desired characteristics. Berzak and Freudenstein [2] stated about optimization criteria for polydyne cam design.

In polydyne cam it is possible to design a cam profile that provides the features desired in kinematic behaviour at the start and end of the stroke. A 2-3 polynomial cam profile is cubic in nature and follower acceleration is discontinuous at the end points. 3-4-5 polynomial cam profile has six polynomial coefficient and a degree of five, provides added control over follower acceleration at the end points. Eight boundary conditions are needed to be specified for finding all the polynomial coefficient in the case of 4-5-6-7 polynomial cam profile. This polynomial cam profile extends the control feature producing zero jerks at the ends [3].

In the present work, analyses of 2-3 polynomial cam profile, 3-4-5 polynomial cam profile and 4-5-6-7 polynomial cam profile are presented. Kinematic and dynamic analyses are carried out using motion equations [3, 5]. The kinematic analysis presents follower characteristics of displacement, velocity and acceleration. Dynamic analysis presents pressure angle, spring force, inertial force and resultant force. Combined plots enlisting the follower characteristics of displacement, velocity and acceleration are presented for above mentioned polynomial cam profiles. Furthermore, plots showing the variation of pressure angle and forces for different cam positions are presented. Next, a complete assembly of cam follower mechanism with 3-4-5 polynomial cam profile is modelled and simulated in SolidWorks software. It is observed that a reduction in cam speed from 650 rpm to 550 rpm, reduces maximum

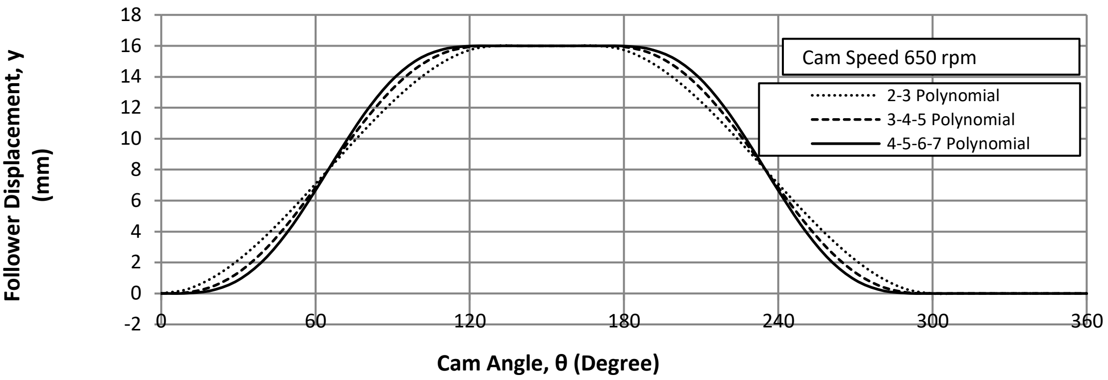

Figure 1: Follower displacement response for various polynomial cam profiles

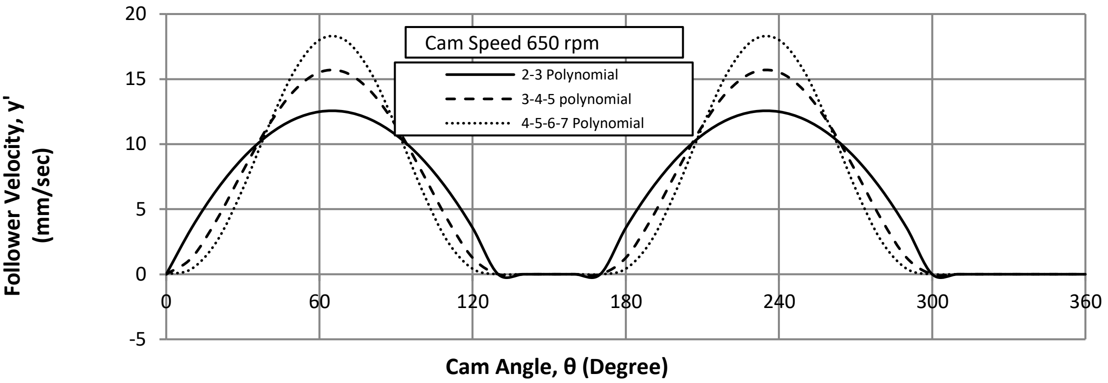

Figure 2: Follower velocity response for various polynomial cam profiles

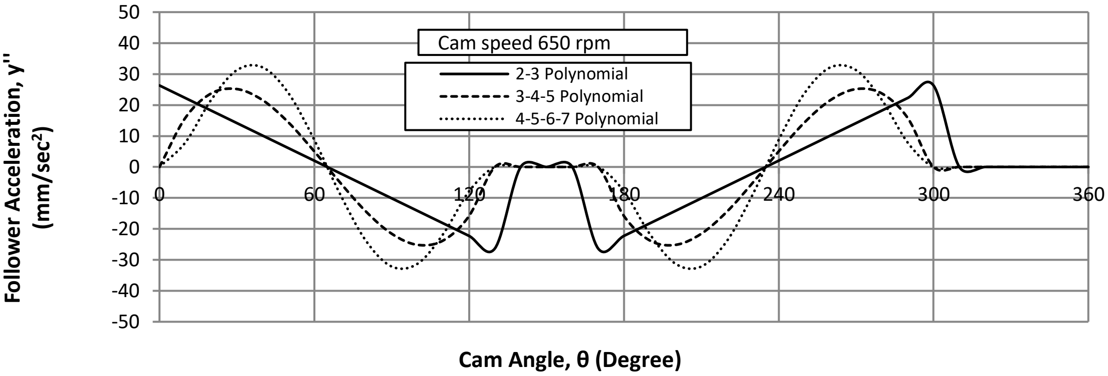

Figure 3: Follower acceleration response for various polynomial cam profiles

follower velocity and maximum follower acceleration by 15.5% and 21.2% respectively.

2. Analysis

2.1 Kinematic Analysis

Assuming Rise Dwell Return Dwell type cam profile, the governing equation of motion for follower displacement is expressed as [3]

2-3 polynomial cam profile $y = h\left[3\left(\frac{\theta}{\beta}\right)^2 - 2\left(\frac{\theta}{\beta}\right)^3\right]$ (1)

3-4-5 polynomial cam profile

$$y = h\left[10\left(\frac{\theta}{\beta}\right)^3 - 15\left(\frac{\theta}{\beta}\right)^4 + 6\left(\frac{\theta}{\beta}\right)^5\right] \quad (2)$$

4-5-6-7 polynomial cam profile

$$y = h\left[35\left(\frac{\theta}{\beta}\right)^4 - 84\left(\frac{\theta}{\beta}\right)^5 + 70\left(\frac{\theta}{\beta}\right)^6 - 20\left(\frac{\theta}{\beta}\right)^7\right] \quad (3)$$

The follower characteristics are calculated for 130^0 rise, 40^0 dwell, 130^0 return and 60^0 dwell. Other parameters are assumed as: lift of follower (h) = 16 mm, speed of cam (N) = 650 rpm and angle of rise (β) = 130°.

Fig. 1 shows the follower displacements for 2-3, 3-4-5 and 4-5-6-7 polynomial cam profiles at uniform cam speed of 650 rpm. As the degree of the polynomial increases the slope of the displacement curve also increases for rise stroke. Consequently, the valve opening duration becomes smaller; alternatively dwell periods at extreme positions of the follower increases.

Fig. 2 shows the corresponding follower velocities for three polynomial cam profiles. It is observed that the peak velocity of the follower increases with an increase in

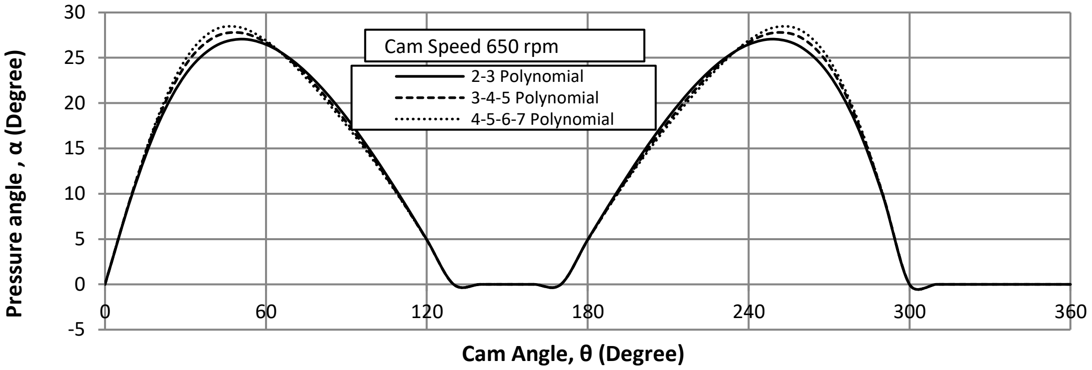

Figure 4: Pressure angle variation with cam position for various polynomial cam profiles

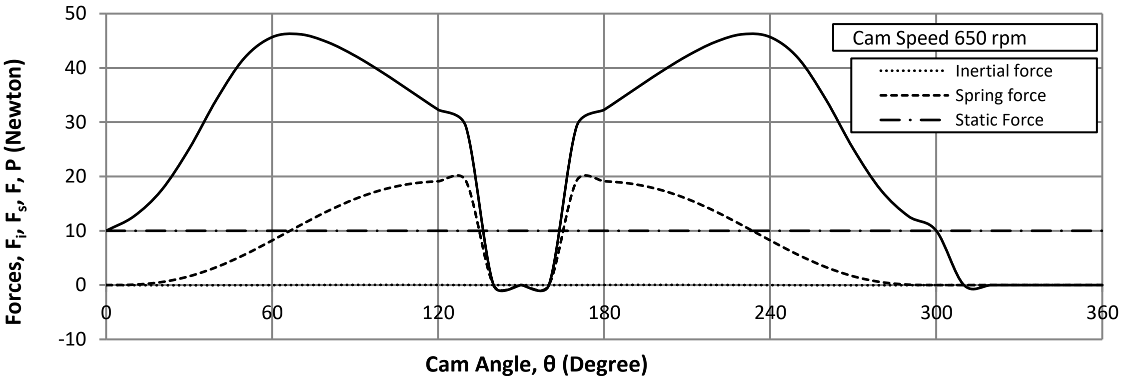

Figure 5: Variations of inertial, spring and resultant forces for 3-4-5 polynomial cam profile

the degree of polynomial. Moreover, the velocity profile of follower is steeper during the middle of rise and return strokes. The peak values of follower velocity for 2-3 polynomial, 3-4-5 polynomial and 4-5-6-7 polynomial cam profiles are 12.49 mm/sec, 15.52 mm/sec and 18.00 mm/sec, respectively.

Fig. 3 shows the corresponding follower accelerations for three polynomial cam profiles. The maximum value of follower acceleration/retardation for 2-3 polynomial , 3-4-5 polynomial and 4-5-6-7 polynomial cam profiles are 26.32 mm/sec^2, 31.26 mm/sec^2 and 32.15 mm/sec^2, respectively. It is observed that acceleration jumps at the ends of rise and return strokes reduces when the degree of polynomial increases. For, 2-3 polynomial the jerks becomes infinite at the ends of strokes; however it reduces drastically (finite) for higher degree polynomials. Therefore, added control over the follower acceleration (alternatively, inertial forces) is achieved for higher degree polynomial cam profiles.

2.2 Dynamic Analysis

Static and dynamic forces are used for the design of different elements of a mechanism. The pressure angle should be between zero and about ±30° for translating followers to avoid jamming in the guide [6]. The pressure angle on the cam profile is calculated as [5]

$$\tan\alpha = \frac{y'(\theta)}{y+r_b+r_r} \qquad (4)$$

As a case study, the 3-4-5 polynomial cam profile is generated for the base circle radius (r_b) 10 mm and follower radius (r_r) 5 mm. The values of inertial forces, spring forces and resultant forces are calculated at 10^0 of cam rotation using the empirical formulae [4]

Inertial Force $(F_I) = -\,(m * y'')$
Spring Force $(F_S) \;= (k * y)$
Resultant Force $(F) = \frac{F_I+F_S+P}{\left[\cos\alpha - \mu\left(\frac{2A+B}{B}\right)\sin\alpha\right]}$ (5)

These are derived with the assumptions that cam, follower, roller pin, guide and roller follower are perfectly rigid; the coefficient of friction between cam and roller follower, roller and roller pin is zero; and roller follower rotates with the cam without slipping. The following values are assumed for the dynamic analysis: m = follower mass (1.6 kg); k = spring constant (1.2 N/mm); P = force due to load (10 N); μ = coefficient of friction (0.1); A = follower overhang (50 mm); B = follower bearing length (10 mm).

Fig. 4 shows the variation of pressure angle with cam angle for three polynomial cam profiles at uniform cam speed of 650 rpm. As the degree of polynomial equation increases successively from 2-3, 3-4-5, 4-5-6-7 there is an increase in the peak value of pressure angle from 27.05^0, 27.78^0 and 28.38^0, respectively. Moreover, the peak position monotonically decreases during the rise stroke and increases during the return stroke. The values of

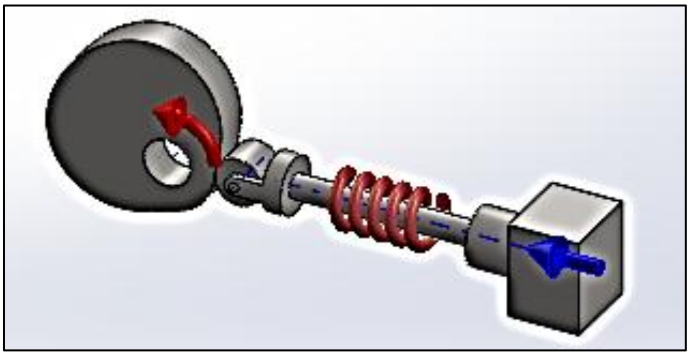

Figure 6: Simulation model of cam follower mechanism with 3-4-5 polynomial cam profile

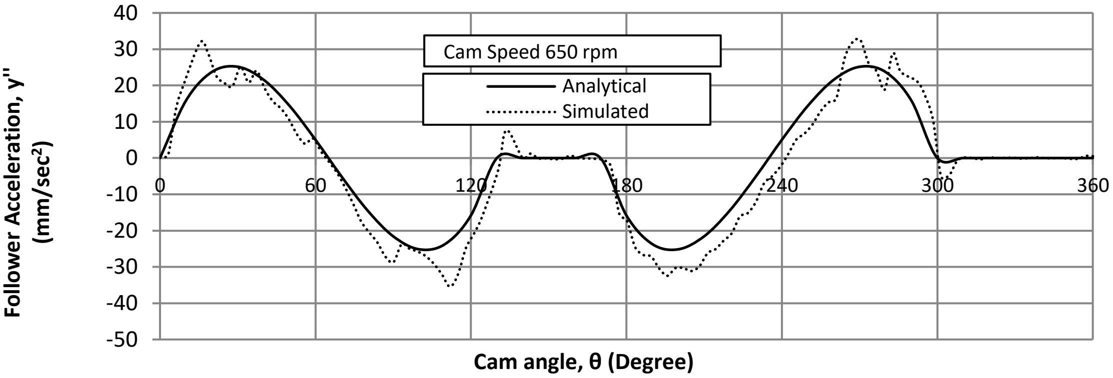

Figure 7: Analytical and simulation responses for follower acceleration

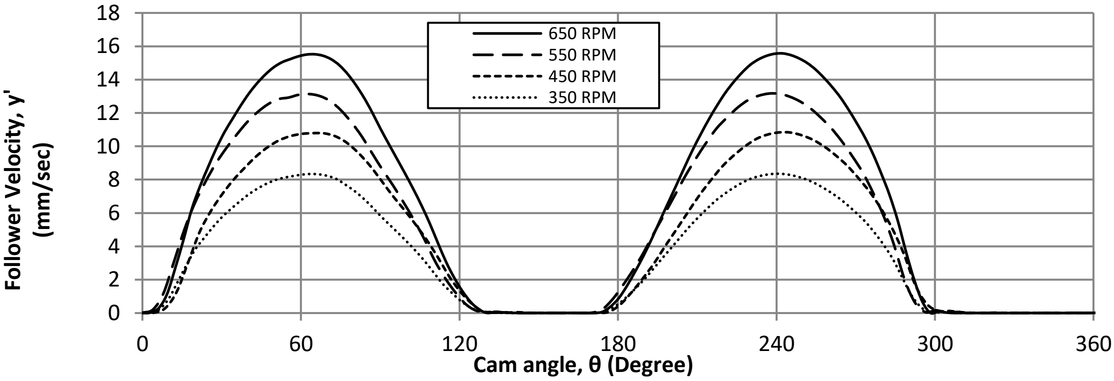

Figure 8: Velocity response of follower with speed as a parameter

pressure angle is within reasonable limits (< ±30°) and the jamming of follower would not take place.

Fig. 5 shows the variation of forces for 3-4-5 polynomial cam profile. Spring force component has major contribution on the resultant force whereas the inertial force has negligible effect. Thus, cam follower mechanisms with a higher follower response rate can be designed using the polynomial profiles.

3. Design and Simulation

3.1 Design

The design and simulation of cam follower mechanism with 3-4-5 polynomial cam profile is carried out. The cam follower mechanism modelling is based on the kinematic and dynamic results. The displacement of the follower is marked at an interval of 10° cam rotation over the base circle. The camshaft radius and cam width are assumed to be 5 mm and 8 mm, respectively.

The cam follower assembly is modelled in SolidWorks software with following major dimensions: follower stem length = 50 mm; roller follower radius = 5 mm; roller follower width = 8 mm; roller pin radius = 1 mm; roller pin width = 8 mm; guide length = 10 mm.

3.2 Simulation

Complete kinematic characteristics of the follower are obtained by simulation of the model shown in Fig. 6. The

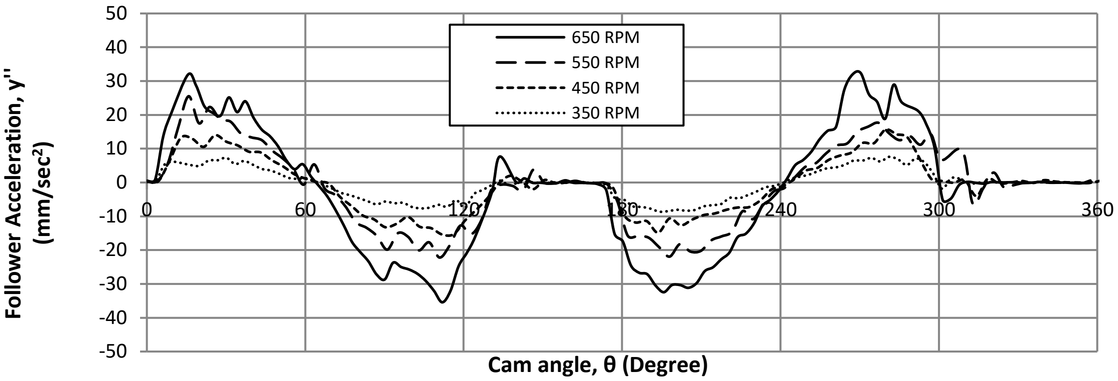

Figure 9: Acceleration response of follower with speed as a parameter

simulation conditions for operating the mechanism assume static force 10 N, spring constant 1.2 N/mm and follower overhang to guide length ratio 5:1. The mechanism is simulated at 650 rpm, 550 rpm, 450 rpm and 350 rpm, respectively.

The simulation response for the follower displacement, velocity and acceleration are in affirmation with the analytical response. Fig. 7 shows the analytical and simulation responses for follower acceleration. Small acceleration peaks are present at the start of the dwell periods (approximately at 130° and 300°) due to the inertia of follower. The probability of the wear of the follower is maximum for these two positions of cam rotation.

the velocity response of follower with speed as a parameter. When cam speed reduces from 650 rpm to 550 rpm the maximum follower velocity reduces by 15.5%. Subsequent reduction in cam speed by 100 rpm reduces the maximum follower velocities by 17.7% and 22.8% respectively. It is observed that the duration of rise and return stroke is unaffected for entire speed range; thus, favours the use of polynomial cam profile at higher speeds.

Fig. 9 shows the follower acceleration response with speed as a parameter. As cam speed reduces, a smoother follower acceleration curve at lower values of acceleration is observed. Moreover, the number of sharp peaks are less; consequently, the jerks are also reduced at lower speeds. Since, the magnitude of acceleration is less; hence, inertial forces are not significant. Hence, at high cam speed the use polynomial cam profiles is preferred.

4. Conclusions

The kinematic analysis of follower with higher degree polynomial cam profile reveals shorter valve opening duration and larger dwell periods. A 2-3 polynomial cam profile shows discontinuous follower acceleration at the ends of the rise and return stroke making it unsuitable at higher speeds. A 3-4-5 polynomial cam profile has an extended control as it provides a zero acceleration at the ends of stokes but no control over the follower jerks. The simulation of cam follower mechanism with 3-4-5 polynomial cam profile shows higher follower response at high cam speeds mainly due to the low inertial forces; hence, should be preferred at higher speeds.

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