ISSN 2348 – 7968

Design of Cam Profile using Higher Order B-Spline

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Abstract

This paper presents the design of Cam profile using B-Spline. B-Spline is used to approximate the basic cycloidal velocity curve which has better motion characteristics. Five degree B-Spline with eight control point is proposed for smooth uniform velocity and acceleration of Cam-follower mechanism which reduces the jerk during motion. A computer-aided design and computer-aided manufacturing (CAD/CAM) system is developed for follower motion, i.e. displacement, velocity, acceleration, jerk and Cam profiles. Simulation results demonstrate the effectiveness of the proposed methodology.

Keywords: Optimized Cam profile, Curves and Spline, Uniform acceleration.

1. Introduction

The Cam and follower is one of the simplest and important mechanism found in modern machinery today. A Cam is a rotating element which gives reciprocating or oscillating motions to another element known as follower and also used to transform rotary motion into a translating or oscillating motion shown in Fig.1.

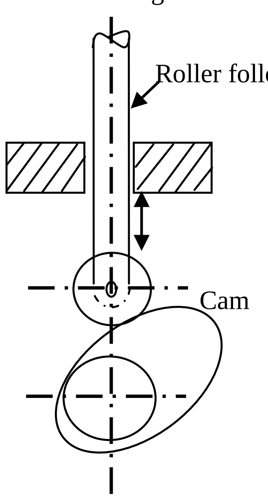


Fig.1 Cam-follower mechanism

Applications of Cam-follower mechanisms are found in almost all mechanical devices and machines especially in the internal combustion engines (Fig. 2). Several studies have been carried out on the design, production and performance of Cams, especially for disk or plate Cams in the past two decades.

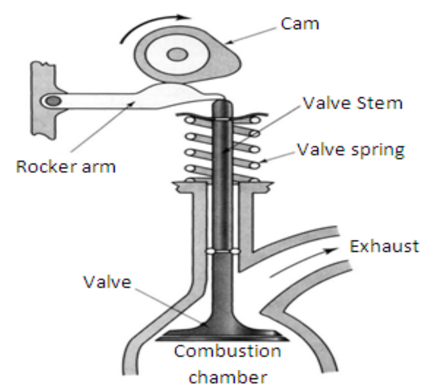


Fig. 2 Cam follower valve mechanism

Initially, all the researchers concentrated on the methodology for describing the surface of the profile (Rothbart 1956). With the advent of powerful computers, work has been concentrated on the development of computer programs to assist in the design and manufacture of Cams. Some of this work includes curve fitting for smoothing the motion curves of the Cam when rotating at high speed. Traditional analysis methods have provided many Cam curves utilized in industries such as the modified sine curve and the modified trapezoidal curve (Makino 1977). These curves not only have a comparatively satisfactory property for general applications but also are defined as a relatively simple expression. An approximate method of calculating the Cam contour for a prescribed acceleration characteristic of a Cam follower has been developed using the reversion of finite differences (Chen 1969). He extended his previous work to refine the prescribed acceleration data so that it improved the numerical accuracy for the use of finite-difference equation (Chen 1972). On the other hand, he applied the finite integration method to synthesize the displacement curve for the same given conditions (Chen 1973). With the advance of CAD technologies, a curve in a parameterized polynomial form or a spline form has been adopted to represent more flexibly a Cam curve (Chen 1982).

Lin et al. (1988) have developed a methodology called combined curves fitting by which Cam profile and NC codes can be automatically generated in the system after specifying the Cam motion function. They established the necessary equation for matching the velocities and accelerations at the curve junctions and Cam profile coordinates for a specified motion of Cam. Sadek and Daadbin (1990) have proposed a method of smoothing the profile curve by using Polynomial curve fitting. The designed Cam produces less vibration than the original Cam and minimizes the tendencies to bounce. However, their work does not deals with the development of diagrams, simulation and the manufacture of Cams algorithm, which produces more economical Computer Numerical Control (CNC) part programs than other interpolation methods. Tsay and Lin (1996) have presented a procedure for the synthesis and analysis of the surface geometry of cylindrical Cams with oscillating roller followers using B-splines. They compared the maximum acceleration and velocity of B-spline Cams with those using traditional curves of Cycloidal and modified sine types to justify their developed method.

Masood (1999) have developed a Computer Aided Design and Manufacturing (CAD/CAM) system which graphically generates the Cam profile on the cylindrical drum, using a B-spline representation of follower curves. Eight different types of follower motion for a translating follower are considered in their research. The kinematic performance is based on the criteria of achieving the lowest levels of velocity and acceleration for each curve. The system is also able to simulate the motion of the designed Cam graphically. Qiu et al. (2005) proposed a universal optimal approach to Cam curve design. With their approach, it is possible to deal simultaneously with multiple objectives for either kinematical or dynamic optimization. Application examples on the kinematical and dynamical optimization of Cam curves to control the residual vibration are presented by them. Demeulenaere and De Schutter (2007) have introduced inertially compensated Cams, which adapted the motion law to the Camshaft speed fluctuation. Sateesh et *al*. (2009) have developed a new follower velocity curve using cubic B-spline with six control points for optimizing the Cam follower motion. They have developed a CAD/CAM system which provides graphical and numerical representation of Cam follower characteristics for all basic and B-splines. It also gives graphical and numerical representation of Cam profile. By comparing the results they found that the B-splines can be used instead of using the regular basic curves for better motion characteristics. They proposed that the maximum acceleration and jerk can be reduced by increasing the degree of B-spline curve and number of control points which has been incorporated in this paper. A new method has been proposed to design Cam profile using five degree B spline with eight control points by approximation of the basic Cycloidal curve which has better motion characteristics for uniform velocity and acceleration of Cam-follower mechanism with minimum jerk.

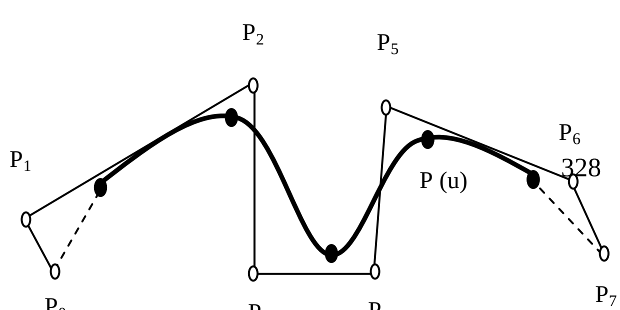
The Paper is organized as following the introduction, Section 2 describe the proposed method of Cam-follower motion synthesis using B-spline. Section 3 illustrates the results obtained from simulation of Cam-follower mechanism. In Section 4 simulation results are analyzed and discussed. Finally conclusions are drawn in Section 5.

2 Synthesis of follower motion curve using B-Spline

When the kinematic and dynamic performances of the Cam-follower mechanisms are to be considered, the follower motion must be carefully synthesized. For example, to reduce the amplitude of the inertial force, the maximum value of the acceleration curve of the follower motion must be as small as possible. One method of improving the follower motion curves would be to represent the curves by parametric B- splines

2.1 B-Spline curve

One of the most versatile tools for modelling curves is the B-splines. B-splines are the synthetic curves which not only interpolate the given set of data points but also approximate them (Cox, 1972). The letter 'B' stands for 'basis' because every spline function can be represented as a linear combination of B-Spline shown in figure 3. It has been widely used in modelling of curves and surfaces in CAD/CAM as a standard tool.



It is a smooth spline which offers a common mathematical form for representation and is used for designing standard curves (conic and quadrics, etc), free form curves and surfaces. They are invariant under the translation, rotation, scaling and perspective as well as parallel projections. One method of improving the follower motion characteristics would be to represent the curves by B-Splines. Mathematically B-splines can be defined by having (k-1) degree and n+1 control point as (Zeid1998):

$$P(u) = \sum_{i=0}^{n} N_{i,k}(u) P_i \quad , 0 \le u \le u_{max} \qquad (1)$$

P (u) is the position on the curve at parameter u, pi is a control point, $N_{i,k}$ (u) is a blending function, which is recursive in nature and polynomial of degree k-1. The range of parameter u depends on the number of control points n+1 and the choice for order of the curve (k), so that u varies from 0 to n+k-2. The Blending function has the property of recursion, which is defined as:

$$N_{i,k}(u) = \frac{[(u-u_i)N_{i,k-1}(u)]}{[u_{i+k-1}-u_i]} + \frac{[(u_{i+k}-u)N_{i+1,k-1}(u)]}{[u_{i+k}-u_{i+1}]} \qquad (2)$$

$$N_{i,1}(u) = 1 \quad \text{if } u_i < u < u_{i+1}$$
$$N_{i,1} = 0 \quad \text{otherwise}$$

with $0 \le j \le n + k$.

$$\begin{Bmatrix} u_j = 0 & \text{if } j < k \\ u_j = j - k + 1 & \text{if } k \le j \le n \\ u_j = n - k + 2 & \text{if } j > n \end{Bmatrix} \qquad (4)$$

number of knot values (m) = n+ k+ 1, i.e. $u_j = [u_0, u_1, u_2, u_3, \dots \dots \dots \dots \dots \dots, u_{n+k}]$,

where, k controls the degree (k-1) of the resulting polynomial in u and also controls the continuity of the curve. The values u_j are called knot values. They relate the parametric variable u and control points (Pi). Blending function is important property of B-spline as it provides the local support. B-Splines have all the three orders of continuity. Their smoothness can be Zero order continuity means curve intersects, first order continuity means tangent at the intersections are same and second order continuity means curvature of the two curves at the intersection are same.

2.2 B-Spline Approximation

The first task in the design of Cam is to select a suitable basic curve which will satisfy the constraints of motion. Here the constraints are the relationship of the motion curves with the Cam rotation angle. Once the basic follower motion curve has been specified, it can then be approximated by B-splines. Here cycloidal curve is selected for approximation because it has smoothest motion among all basis motion curves. During approximation following steps are carried out:

1. Create the basic curve of selected follower motion (cycloidal, parabolic etc.)
2. Divide the angle of interval of the curve into seven equal parts. This will create eight points v_0, v_1, v_2, v_3, v_4, v_5, v_6, and v_7 lying on the curve. These eight control points are selected for specified rise angle of return Cam angle.
3. The point on the curve is then defined by using the equation

$$V(u) = \sum_{i=0}^{n} N_{i,k} V_i \, , \quad 0 \le u \le 3 \qquad (5)$$

Using equations (2) to (5) the parametric equations of velocity curve for three segments can be defined as:

For $0 \le u \le 1$,

$V_1(u) = (-u^5 + 5u^4 - 10u^3 + 10u^2 - 5u + 1)V_0 + (31u^5/16 - 75u^4/8 + 35u^3/2 - 15u^2 + 5u)V_1 + (425u^4/72 - 575u^5/432 - 55u^3/6 + 5u^2)V_2 + (37u^5/72 - 65u^4/36 + 5u^3/3)V_3 + (5u^4/18 - 5u^5/36)V_4 + (u^5/54)V_5$ (6)

for $1 \le u \le 2$,

$V_2(u) = (-u^5/16 + 5u^4/8 - 5u^3/2 + 5u^2 - 5u + 2)V_1 + (73u^5/432 - 115u^4/72 + 35u^3/6 - 10u^2 + 15u/2 - 3/2)V_2 + (-17u^5/72 + 35u^4/18 - 35u^3/6 + 15u^2/2 - 15u/4 + 3/4)V_3 + (17u^5/72 - 115u^4/72 + 15u^3/4 - 15u^2/4 + 15u/8 - 3/8)V_4 - (73u^5/432 - 15u^4/16 + 15u^3/8 - 15u^2/8 + 15u/16 - 3/16)V_5 + (u^5/16 - 5u^4/16 + 5u^3/8 - 5u^2/8 + 5u/16 - 1/16)V_6$ (7)

and for $2 \le u \le 3$,

$V_3(u) = (5u^4/18 - u^5/54 - 5u^3/3 + 5u^2 - 15u/2 + 9/2)V_2 + (5u^5/36 - 64u^4/36 + 55u^3/6 - 45u^2/2 + 105u/4 - 45/4)V_3 + (425u^4/72 - 37u^5/72 - 105u^3/4 + 225u^2/4 - 465u/8 + 189/8)V_4 + (575u^5/432 - 225u^4/16 + 465u^3/8 - 945u^2/8 + 1905u/16 -$

$765/16)V_5 + (315u^4/16 - 31u^5/16 - 635u^3/8 + 1275u^2/8 - 2555u/16 + 1023/16)V_6 + (u^5 - 10u^4 + 40u^3 - 80u^2 + 80u - 32)V_7$ (8)

$V_1(u)$, $V_2(u)$, and $V_3(u)$ are the three segments of desired velocity curve of follower with respect to Cam angle in specified range of Cam motion.
Considering θ= angle of rotation of Cam, r_1 = rise angle and r_2 = return angle, the parameter $u = \left(\frac{\theta}{r_1}\right)$, where θ varies from 0 to r_1 or $u = \left(\frac{\theta}{r_2}\right)$ where varies from 0 to r_2. Now displacement (S) of the follower is obtained by integrating above three segments of velocity equations (6) to (8) with respect to time (t).

$$S(u) = \int V(u)dt + C = (r_1/w)\{\int V(u)du\} + C \quad (9)$$

where,
w=Angular velocity of the follower =(2πN/60),N= Speed of Cam, C= constant, $R_{11} = (180w/\pi r_1)$

$$S_1(u) = \int V_1(u)\,dt + C_1 = (r_1/w)\{\int V_1(u)du\} + C_1$$

$$S_2(u) = \int V_2(u)\,dt + C_2 = (r_1/w)\{\int V_2(u)du\} + C_2$$

$$S_3(u) = \int V_3(u)\,dt + C_1 = (r_1/w)\{\int V_3(u)du\} + C_3 \quad (10)$$

Now, for finding the integrating constants (C_1, C_2 and C_3) for all the three segments, following three conditions are assumed.
Initial displacement is zero i.e.

$$S_1(u) = 0, \quad \text{at } u=0 \quad (11)$$

End point of the first part curve and starting point of the second part curve are same i.e.

$$S_1(u) = S2(u), \quad \text{at } u=1 \quad (12)$$

End point of the second part curve and starting point of the third part curve are same i.e.

$$S_2(u) = S3(u), \quad \text{at } u=2 \quad (13)$$

The three integrating constants obtained by substituting the values of $S_1(u)$, $S_2(u)$ and $S_3(u)$ into equation (11) to (13) from equation (10) are:

$C_1=0$,

$$C_2 = (1/R_{11})\{0.167V_0 - 0.33V_1 + 0.25V_2 - 0.625V_3 - 0.0625V_4 - 0.03125V_5 + 0.0104V_6\}$$

$$C3 = (1/R_{11})\{0.167V_0 + 0.337V_1 - 1.7491V_2 - 3.374V_3 - 8.0625V_4 - 15.96V_5 - 21.3196V_6 + 10.667V_7\}$$

Where,
$R_{11} = (3*180*w/\pi*r_1)$ and parameter $u = 3*(\theta/r_1)$
Finally the displacement equation, obtained for the three segment of the curve can be written as:

For $0 \le u \le 1$,

$$S_1(u) = (1/R_{11})\{(u^5 - u^6/6 - 5u^4/2 + 10u^3/3 - 5u^2/2 + u)V_0 + (31u^6/96 - 75u^5/40 + 35u^4/8 - 5u^3 + 5u^2/2)V_1 + (85u^5/72 - 575u^6/2592 - 55u^4/24 + 5u^3/3)V_2 + (37u^6/432 - 13u^5/36 + 5u^4/12)V_3 + (u^5/18 - 5u^6/216)V_4 + (u^6/324)V_5)\} \quad (14)$$

For $1 \le u \le 2$,

$$S_2(u) = C_2 + (1/R_{11})\{(u^5/8 - u^6/96 - 5u^4/8 + 5u^3/3 - 5u^2/2 + 2u)V_1 + (73u^6/2592 - 115u^5/360 + 35u^4/24 - 10u^3/3 + 15u^2/4 - 3u/2)V_2 + (7u^5/18 - 17u^6/432 - 35u^4/24 + 15u^3/6 - 15u^2/8 + 3u/4)V_3 + (17u^6/432 - 23u^5/72 + 15u^4/16 - 15u^3/12 + 15u^2/16 - 3u/8)V_4 + (3u^5/16 - 73u^6/2592 - 15u^4/32 + 15u^3/24 - 15u^2/32 + 3u/16)V_5 + (u^6/96 - u^5/16 + 5u^4/32 - 5u^3/24 + 5u^2/32 - u/16)V_6 \quad (15)$$

And for $2 \le u \le 3$,

$$S_3(u) = C3 + (1/R_{11})\{(u^5/18 - u^6/324 - 5u^4/12 + 5u^3/3 - 15u^2/4 + 9u/2)V_2 + (5u^6/216 - 13u^5/36 + (55u^4/24 - 15u^3/2 + 105u^2/8 - 45u/4)V_3 + (85u^5/72 - 37u^6/432 - 105u^4/16 + 75u^3/4 - 465u^2/16 + 189u/8)V_4 + (575u^6/2592 - 45u^5/16 + 465u^4/32 - 315u^3/8 + 1905u^2/32 - 765u/16)V_5 + (63u^5/16 - 31u^6/96 - 635u^4/32 + 425u^3/8 - 2555u^3/32 + 1023u/16)V_6 + (u^6/6 - 10u^5/5 + 10u^4 - 80u^3/3 + 40u^2 - 32u)V_7\} \quad (16)$$

Similarly acceleration equations for the three segments are obtained by differentiating velocity equations V(u) with respect to time(t)

$$A(u) = dV(u)/dt = (w/r_1)\{dV(u)/du\} \quad (17)$$

Jerk can be obtained by differentiating the acceleration equations A(u) with respect to time (t)

$$J(u) = dA(u)/dt = (w/r_1)\{dA(u)/du\} \quad (18)$$

Acceleration equations for the three parts of the curves can be written as:

For $0 \le u \le 1$,

$$A_1(u) = R_{11}\{(-5u^4 + 20*u^3 - 30u^2 + 20u - 5)V_0 + (155u^4/16 - 75u^3/2 + 105u^2/2 - 30u + 5)V_1 + (425u^3/18 - 2875u^4/432 - 55u^2/2 + 10u)V_2 +$$

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$(185u^4/72 - 65u^3/9 + 5u^2)V_3 + (10u^3/9 - 25u^4/36)V_4 + (5u^4/54)V_5\}$ (19)

for $1 \le u \le 2$,

$A_2(u) = R_{11}\{(5u^3/2 - 5u^4/16 - 15u^2/2 + 10u)V_1 + (365u^4/432 - 115u^3/18 + 35u^2/2 - 20u + 15/2)V_2 + (70u^3/9 - 85u^4/72 - 35u^2/2 + 15u - 15/2)V_3 + (85u^4/72 - 115u^3/18 + 45u^2/4 - 15u/2 + 15/8)V_4 + (15u^3/4 - 365u^4/432 - 45u^2/8 + 15u/4 - 15/16)V_5 + (5u^4/16 - 5u^3/4 + 15u^2/8 - 5u/4 + 5/16)V_6\}$ (20)

and for $2 \le u \le 3$,

$A_3(u) = R_{11}\{(10u^3/9 - 5u^4/54 - 5u^2 + 10u - 15/2)V_2 + (25u^4/36 - 64u^3/9 + 55u^2/2 - 45u + 105/4)V_3 + (425u^3/18 - 185u^4/72 - 315u^2/4 + 225u/2 - 465/8)V_4 + (2875u^4/432 - 225u^3/4 + 1395u^2/8 - 945u/4 + 1905/16)V_5 + (315u^3/4 - 155u^4/16 - 1905u^2/8 + 1275u/4 - 2555/16)V_6 + (5u^4 - 40u^3 + 120u^2 - 160u + 80)V_7\}$ (21)

Similarly Jerk equations for the three parts of the curves can be written as:

For $0 \le u \le 1$,

$J_1(u) = R_{11} R_{11} \{(-20u^3 + 60u^2 - 60u + 20)V_0 + (155u^3/4 - 225u^2/2 + 105u - 30)V_1 + (425u^2/6 - 2875u^3/108 - 55u + 10)V_2 + (185u^3/18 - 65u^2/3 + 10u)V_3 + (10u^2/3 - 25u^3/9)V_4 + (10u^3/27)V_5\}$ (22)

for $1 \le u \le 2$,

$J_2(u) = R_{11}R_{11}\{(15u^2/2 - 5u^3/4 - 15u^2 + 10)V_1 + (365u^3/108 - 115u^2/6 + 35u - 20)V_2 + (70u^2/3 - 85u^3/18 - 35u + 15)V_3 + (85u^3/18 - 115u^2/6 + 45u/2 - 15/2)V_4 + (45u^2/4 - 365u^3/108 - 45u/2 + 15/4)V_5 + (5u^3/4 - 15u^2/4 + 15u/4 - 5/4)V_6\}$ (23)

and for $2 \le u \le 3$,

$J_3(u) = R_{11}R_{11}\{(10u^2/3 - 10u^3/27 - 10u + 10)V_2 + (25u^3/9 - 64u^2/3 + 55u - 45)V_3 + (425u^2/6 - 185u^3/18 - 315u/2 + 225/2)V_4 + (2875u^3/108 - 675u^2/4 + 1395u/4 - 945/4)V_5 + (945u^2/4 - 155u^3/4 - 1905u/4 + 1275/4)V_6 + (20u^3 - 120u^2 + 240u - 160)V_7\}$ (24)

Now displacement equations (16) to (18) are used to generate the Cam profile. Considering the Translating-Radial roller follower, Rectangular co-ordinates for trace points for the generation of Cam profile can be obtained by

$$X = (R_p + S)\sin\theta$$

$$Y = (R_p + S)\cos\theta \quad (25)$$

Where Rp = prime circle radius.

3 Simulation results

A program is developed using MATLAB (R2009) to obtain simulation results of proposed methodology. The following inputs are required to get simulation results.

1. Speed of Cam rotation (N)
2. Direction of follower (lift/return)
3. Interval angle for each segment of motion curve.
4. A set of eight Control points for the specified rise motion for constant lift (V_i)

The program is tested for the simulation of Cam-follower system in following motion duration:

Rise angle = 120^0, Dwell 1 = 60^0, Return angle=120^0, Dwell 2 = 60^0, Speed (N) =100 RPM, Lift=20mm.

For Speed (N) = 100 RPM, The velocity control points (V_i) used to get the required maximum lift of 20mm are:

V_i = (0, 0, 60, 240, 240, 60, 0, 0) mm/s,

Where, i = 0, 1, 2, 3, 4, 5, 6, 7

Velocity control points are selected such that the equivalent velocity and the acceleration are continuous and have minimum jerk values for constant lift. User required motion and Cam speed can be used for analysis of the result. To obtain the equivalent B-spline by approximating basic Cycloidal motion, the first two velocity control points are taken as minimum and last two velocity control points are set to maximum velocity.

The developed program computes the Cam profile to generate the specified follower motion and output gives the following information:

1. Graphical display of Displacement, Velocity, Acceleration and Jerk diagrams and Cam profile for equivalent B-Spline.
2. Numerical values of Displacement, Velocity, Acceleration and Jerk and Cam profile co-ordinate for each degree of Cam rotation.

4 Analysis & Result discussions

The simulation results obtained for Cam speed N is taken as 100 RPM. The follower displacement, velocity, acceleration and jerk responses are shown in Figure 4, 5, 6 and 7 respectively. These Figures illustrate the characteristic response of the specified follower motion with respect to Cam rotation angle for approximated B-

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spline Cycloidal motion. The characteristics of Cam-follower using approximated five degree B-spline with eight control points gives the more accurate results than the other basic and cubic B-spline. The graphical representation of generated Cam profile for approximated B-spline curve is shown in Figure 8. The numerical values of the motion characteristics for successive five degree of Cam rotation obtained from simulation results are shown in Table 1 and Table 3.

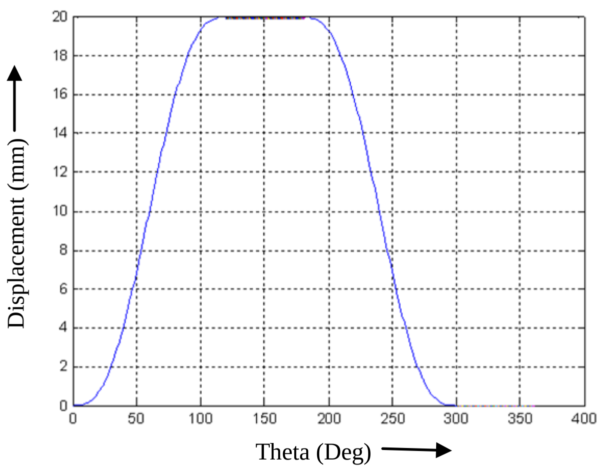

Fig.4 Displacement for cycloidal motion equivalent B-spline curve

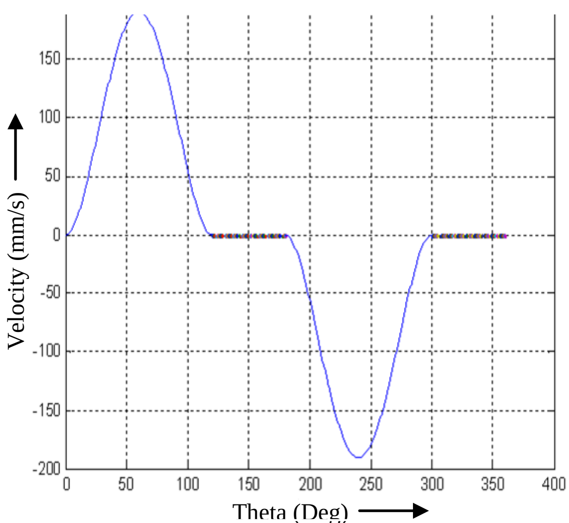

Fig.5 Velocity for Cycloidal motion equivalent B-spline curve

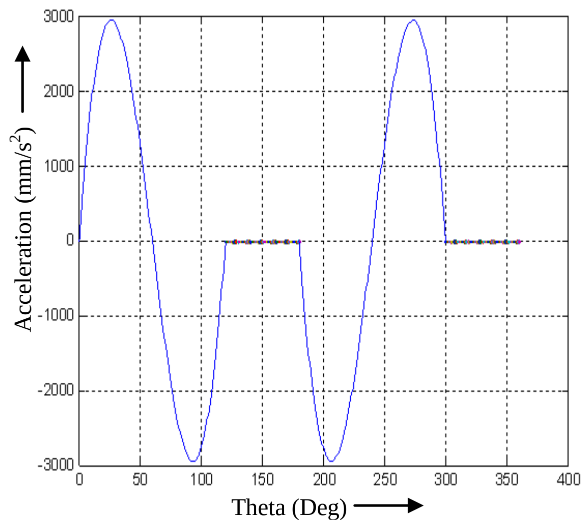

Fig.6 Acceleration for Cycloidal motion equivalent B-spline curve

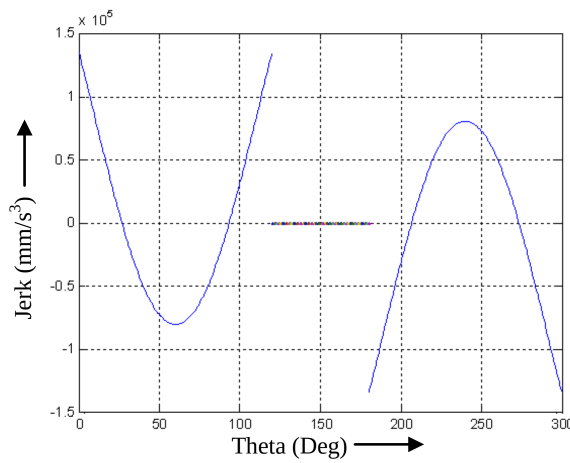

Fig.7 Jerk for Cycloidal motion equivalent B-spline curve

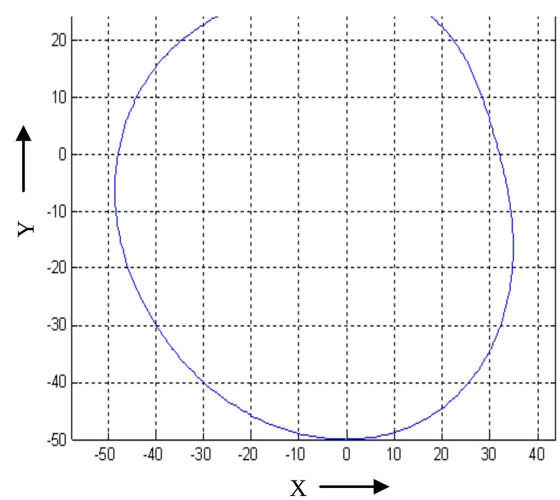

Fig.8 Pitch profile for equivalent B-spline curve

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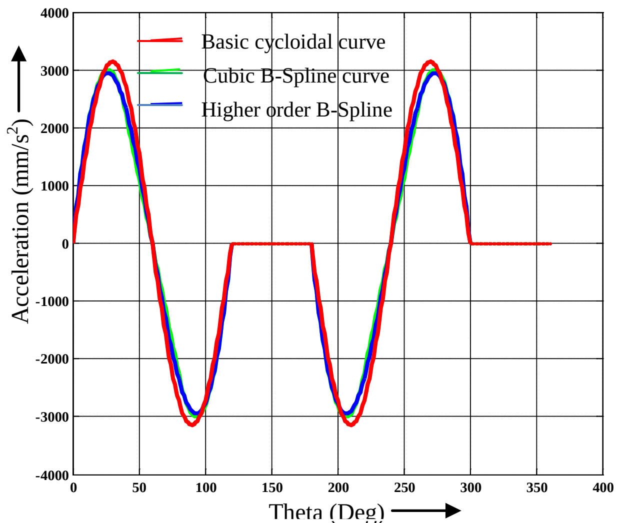

Fig.9 Comparison of Acceleration for basic and equivalent B-spline curves

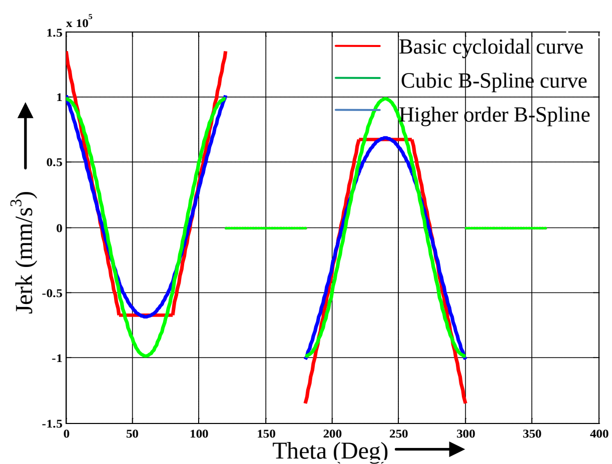

Fig.10 Comparison of Jerk for basic and equivalent B-spline curves

Table 1 Values of motion characteristics for specified rise motion

θ	S(mm)	V(mm/s)	A(mm/s^2)	J(x10^5) (mm/s^3)
0	0	0	0	1.35
5	0.0124	4.3918	1018.3	0.8635
10	0.0943	16.3684	1819.7	0.8306
15	0.3012	34.1136	2402.9	0.4979
20	0.6738	55.8203	2771.5	0.3164
25	1.2377	79.7319	2933.9	0.0985
30	2.0042	104.1833	2903.7	-0.0929
35	2.9713	127.6422	2699.2	-0.2676
40	4.125	148.75	2343.8	-0.4172
45	5.4407	166.3632	1865.5	-0.5345
50	6.8855	179.5850	1294.9	-0.6184
55	8.4198	187.7744	662.8	-0.6687
60	10	190.5469	0	-0.6855
65	11.5802	187.7744	-662.8	-0.6687
70	13.1145	179.5850	-1294.9	-0.6184
75	14.5593	166.3632	-1865.5	-0.5345
80	15.875	148.75	-2343.8	-0.4171
85	16.9937	127.6422	-2699.2	-0.2676
90	17.9608	104.1833	-2903.7	-0.0929
95	18.7273	79.7319	-2933.9	0.0985
100	19.2912	55.8203	-2771.5	0.2982
105	19.6638	34.1136	-2402.9	0.4979
110	19.8707	16.3684	-1819.7	0.6891
115	19.9526	4.3918	-1018.3	0.8635
120	19.965	0	0	1.35

Table 2 Comparison of maximum acceleration for various follower motions at different speed inputs.

Type of motion	Maximum acceleration (mm/s^2)		
Cam speed (RPM)	100	200	500
Simple harmonic motion	2467.4	9869.6	61685.0
Cycloidal	3141.2	12566.3	78539.8
4-5-6-7 polynomial	3756.4	15025.6	93910.3
Double harmonic motion	4934.8	19739.2	123370
Cubic B-spline	2999.5	11998.1	74988.2
5thdegree B-spline (approximation to Cycloidal)	2944.0	11776.0	73601.0
% Reduction over Cycloidal motion	6.28%		
% Reduction over Cubic B-spline motion	1.85%		

Table 3 Numerical value's of cam profile co-ordinate values (x, y coordinates, mm)

θ	X	Y
0	0.00	30.00
5	-2.6158	29.8982
10	-5.2258	29.6372
15	-7.8427	29.2692
20	-10.4915	28.825
25	-13.2025	28.3128
30	-16.0038	27.7193
35	-18.9144	27.0126

40	-21.9395	26.1465
45	-25.0668	25.0668
50	-28.2647	23.7169
55	-31.4832	22.0448
60	-34.6554	20.0083
65	-37.7019	17.5807
70	-40.5349	14.7535
75	-43.0644	11.5391
80	-45.2041	7.9707
85	-47.9908	0
90	-48.573	-4.2496
95	-48.574	-8.5649
100	-48.0032	-12.8624
105	-46.8943	-17.0681
110	-45.3026	-21.1249
115	-43.2998	-24.9991
120	-47.9908	0

The simulation results obtained from proposed method using five degree polynomial B-spline with eight control points have been compared with the results obtained by Sateesh et al. (2009) using various basic curves and cubic B-spline with six control points. The response of displacement and velocity motion characteristics are almost same as obtained by other authors. Fig. 9 illustrated the comparison of motion characteristic curves of the Cam-follower for the maximum acceleration. By the analysis of the motion characteristic curves of the Cam-follower for the maximum acceleration, it is clear that the developed methodology using higher order B-spline provides better results than the results produced by Sateesh et al. (2009) for the maximum acceleration using basic cycloidal and cubic B-spline.

Fig. 10 illustrated the comparison of motion characteristics curves of the Cam-follower for the maximum jerk. By the analysis of the motion characteristics curves of the Cam-follower for the maximum jerk, again it is found that the proposed method using higher order B-spline provides better results than the results produced by Sateesh et al. (2009).

Numerical values obtained by developed methodology for maximum acceleration using higher order B-spline are compared with the numerical value obtained by Sateesh et al. (2009) in Table 2. By the analysis it is found that, the fifth order B-spline (approximation of cycloidal) has reduced the maximum acceleration by 6.28% as compared to basic cycloidal motion and 1.85% as compared to cycloidal approximated cubic B-spline.

From the above results Five degree B-spline with eight control points are thus, found to be more advantageous than the basic cycloidal and cubic B-spline even in the high speed applications. Users can choose the proposed five degree B-spline with eight control points instead of regular basic curves and cubic B-spline to improve the design of Cam profile and motion characteristics of Cam follower mechanisms. They can also select the desired velocity and can change the shape of the velocity curve by changing the control points. This unique property makes it different to the other regular basic curves and splines, and it provides continuous acceleration which is better than the regular basic curves or spline.

5. Conclusions

From theoretical, numerical and simulation analysis it is found that the nature of curves play an important role in designing Cam-follower mechanism. The flexible curve is useful to design Cam profile with high velocity, uniform acceleration and jerk less smooth motion. The developed free form curve has unique motion characteristics and it permits local change of shape by changing the control points. The motion characteristics of the desired smooth Cam profile have been generated by using developed five degree B-Spline free form curve with eight control points. The designed Cam-follower system is found to be efficient and provides better continuity with uniform acceleration as compared to the basic cycloidal motion curve. The developed methodology is simple, effective and efficient to design a Cam profile and Cam-follower mechanism with high velocity, uniform acceleration and minimum jerk.

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