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PROFILE SIMULATION SOFTWARE FOR TRIGONOMETRIC AND POLYNOMIAL CAMS DESIGN

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ABSTRACT

This paper discusses the development of unique software for the design of various cam profiles for the plate cam operating a flat face follower. The method employed in this work is that of generating geometrical cam coordinates using standard cam motions, thereby avoiding the problem of undercutting resulting from graphical layout methods for similar cam and follower types. Determination of critical design output parameters were carried out by the developed software computational algorithm. The software was validated by using it to simulate a number of standard cases. For the standard case having the follower profile Dwell (200^0)-Rise (280^0)-Dwell (300^0)-Return (360^0) and performing cycloid rise and return motions, the prime circle radius for the cam profile and the face width of the follower were calculated as 55.72mm and 33.76mm while the maximum and minimum follower velocities were 13.70 mm/rad and –10.27 mm/rad respectively. These values, as well as those obtained for other standard cases simulated, were found to be in agreement with earlier works done in this area of research

Keywords: Cam Design, Software Development, Profile Simulation

INTRODUCTION

In many engineering applications and operations the production of a prescribed motion to carry out specific operations is of primary importance. A cam mechanism is a device whose function is to produce, by means of a contoured cam surface, a prescribed motion of the output link of the linkage, called the Follower. Cams are used in many machines as well as reciprocating engines, compressors, and rotating machinery and in many other applications. One of the problems encountered in cam design, is that of the large number of design options due to the various types of cams, followers and cam motions available. An invaluable contribution to the design of cam profile design has therefore been made in this work by developing CAD software capable of generating cam profiles for different types of follower motions and cam motions for the plate cam and flat face follower. This work has emanated from earlier works in the areas of dynamic analysis of cam systems (Hamilton and fed, 1978; Tesar and Mathew, 1976; Andrezej, 1980; Robert, 1987);, force and torque analysis (Virgil, 1965.); cam profile design (Shigley, 1995; Olaniyi, 1997; Udoh, 2001). The standard follower displacement profiles considered in this work are (i) Dwell-Rise-Dwell-Return (D-R-D-R) (ii) Rise-Return-Rise (R-R-R) (iii) Dwell-Rise-Return (D-R-R) (iv) Rise-Dwell-Return (R-D-R). The standard cam motion equations used in this work are those which address most high speed cam motion requirements (Shigley, 1998.) The cam motions are in pairs of rise and return motions. They are simple harmonic motion (SHM), cycloid motion, 3-4-5 polynomial motion and eight order polynomial motion. The main concern in this work is the development of a computer-based method for the design of geometrical shapes of cams for various design options as specified by the relevant design criteria.

CAM DESIGN: MATHEMATICAL PROCEDURE

The design of cam profiles for the combinations considered in this work entails: (i) standard cam motions (ii) design output parameters.

Standard Cam Motions

The displacement profile of the follower and its derivatives y, y^{1} and y^{11} with respect to the specified cam angles θ at any point of rotation for the considered cam motions in this work were calculated as follows:

(i) **Simple-Harmonic-Motion**

Rise

$$Y = \frac{L}{2}\left(1 - \cos\frac{\pi\theta}{\beta} \right)$$

$$Y' = \frac{\pi L}{2\beta}\sin\frac{\pi\theta}{\beta}$$

$$\dots\dots\dots(1a)$$

$$Y'' = \frac{\pi^2 L}{2\beta^2}\cos\frac{\pi\theta}{\beta}$$

Return

$$Y = \frac{L}{2}\left(1+\cos\frac{\pi\theta}{\beta}\right)$$

$$Y' = -\frac{\pi L}{2\beta}\sin\frac{\pi\theta}{\beta} \qquad \dots\dots\dots(1b)$$

$$Y'' = -\frac{\pi^2 L}{2\beta^2}\cos\frac{\pi\theta}{\beta}$$

(ii) **Cycloid – Motion**

Rise

$$Y = L\left(\frac{\theta}{\beta} - \frac{1}{2\pi}\sin\frac{2\pi\theta}{\beta}\right)$$

$$Y' = \frac{L}{\beta}\left(1-\cos\frac{2\pi\theta}{\beta}\right) \qquad \dots\dots\dots(2a)$$

$$Y'' = \frac{2\pi L}{\beta^2}\sin\frac{2\pi\theta}{\beta}$$

Return

$$Y = L\left(1-\frac{\theta}{\beta} + \frac{1}{2\pi}\sin\frac{2\pi\theta}{\beta}\right)$$

$$Y' = -\frac{L}{\beta}\left(1-\cos\frac{2\pi\theta}{\beta}\right)$$

$$\dots\dots\dots(2b)$$

$$Y'' = -\frac{2\pi L}{\beta^2}\sin\frac{2\pi\theta}{\beta}$$

(iii) **3-4-5 POLYNOMIAL**

Rise:

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

$$y' = \frac{h}{\beta}\left[30\left(\frac{\theta}{\beta}\right)^{2} - 60\left(\frac{\theta}{\beta}\right)^{3} + 30\left(\frac{\theta}{\beta}\right)^{4}\right]$$

............(3a)

$$y'' = \frac{h}{\beta^{2}}\left[60\left(\frac{\theta}{\beta}\right) - 180\left(\frac{\theta}{\beta}\right)^{2} + 120\left(\frac{\theta}{\beta}\right)^{3}\right]$$

Fall:

$$y = h\left[1 - 10\left(\frac{\theta}{\beta}\right)^{3} - 15\left(\frac{\theta}{\beta}\right)^{4} + 6\left(\frac{\theta}{\beta}\right)^{5}\right]$$

$$y' = -\frac{h}{\beta}\left[30\left(\frac{\theta}{\beta}\right)^{2} - 60\left(\frac{\theta}{\beta}\right)^{3} + 30\left(\frac{\theta}{\beta}\right)^{4}\right]$$

............(3b)

$$y'' = -\frac{h}{\beta^{2}}\left[60\left(\frac{\theta}{\beta}\right) - 180\left(\frac{\theta}{\beta}\right)^{2} + 120\left(\frac{\theta}{\beta}\right)^{3}\right]$$

(iv) 8th Order POLYNOMIAL

RISE ....(4a)

$$y = h\left[6.09755\left(\frac{\theta}{\beta}\right)^{'} - 20.78040\left(\frac{\theta}{\beta}\right)^{5} + 26.73155\left(\frac{\theta}{\beta}\right)^{6} - 13.60965\left(\frac{\theta}{\beta}\right)^{7} + 2.56095\left(\frac{\theta}{\beta}\right)^{8}\right]$$

$$y' = \frac{h}{\beta}\left[18.29265\left(\frac{\theta}{\beta}\right)^{2} - 103.902\left(\frac{\theta}{\beta}\right)^{4} + 160.3893\left(\frac{\theta}{\beta}\right)^{5} - 95.26755\left(\frac{\theta}{\beta}\right)^{6} + 20.4876\left(\frac{\theta}{\beta}\right)^{7}\right]$$

$$y'' = \frac{h}{\beta^{2}}\left[36.5853\left(\frac{\theta}{\beta}\right) - 415.608\left(\frac{\theta}{\beta}\right)^{3} + 801.9465\left(\frac{\theta}{\beta}\right)^{4} - 571.6053\left(\frac{\theta}{\beta}\right)^{5} + 143.4132\left(\frac{\theta}{\beta}\right)^{6}\right]$$

FALL: ....(4b)

$$y = h\left[1 - 2.63415\left(\frac{\theta}{\beta}\right)^{2} 2.78055\left(\frac{\theta}{\beta}\right)^{5} + 3.17060\left(\frac{\theta}{\beta}\right)^{6} - 6.87795\left(\frac{\theta}{\beta}\right)^{7} + 2.56095\left(\frac{\theta}{\beta}\right)^{8}\right]$$

$$y'' = \frac{h}{\beta}\left[5.26830\left(\frac{\theta}{\beta}\right) - 13.90275\left(\frac{\theta}{\beta}\right)^{4} - 19.02360\left(\frac{\theta}{\beta}\right)^{5} + 48.14565\left(\frac{\theta}{\beta}\right)^{6} + 20.48760\left(\frac{\theta}{\beta}\right)^{7}\right]$$

$$y'' = \frac{h}{\beta^{2}}\left[+5.26830 - 55.61100\left(\frac{\theta}{\beta}\right)^{3} - 95.11800\left(\frac{\theta}{\beta}\right)^{4} + 288.87390\left(\frac{\theta}{\beta}\right)^{5} - 143.41320\left(\frac{\theta}{\beta}\right)^{6}\right]$$

Where L= maximum lift for displacement of follower; θ=angles of cam rotation; β= angular intervals between stages of cam angles.

Determination of Output Design Parameters

A schematic of the analysed cam and follower at point of contact is shown in figure 1. R_o (the Prime circle radius) is the radius of the smallest circle drawn with center at the cam rotation axis and tangent to the pitch curve. C denotes the instantaneous center of curvature while the radius of curvature corresponding to the current contact point is shown as ρ. The coordinates of the contact point in a coordinate system attached to the cam are depicted as u, v. The distance of travel of the point of contact either side of the cam rotation center is given as s while ε is offset of the follower face and θ is the angle of cam rotation. The displacement of follower is y and r is the distance of the instantaneous center of curvature to the cam center.

Prime Circle Radius (Ro)

Based on works done earlier (Andrezej, 1980; Hamilton, 1991; Shigley, 1980.) we can write a loop closure equation using vectors shown in Figure1. Equation (5) resulting from the complex analysis of the vectors has been used in estimating the values of Ro.

$$Ro > (\rho min - Y - Y'')max \qquad (5)$$

Face Width (Fw)

The Face width of the flat face follower is determined based on equation (6), which is obtained from another loop closure equation analysis of figure 1 (Shigley, Hamilton and Andrezej)

$$\text{Face Width} > Y'(max) - Y'(min) \qquad (6)$$

Coordinates of Cam Profiles

Considering Figure 1 again and using complex polar-notations we can write another loop-closure equation using the vectors u and v (Hamilton, Shigley, 1980). To obtain equation 7a and 7b below

$$u = (Ro+Y)\sin\theta + Y'\cos(\theta) \qquad 7a$$

$$v = (Ro+Y)\cos\theta - Y'\sin(\theta) \qquad 7b$$

Equations 7a and 7b are the equations used to generate the profile or geometry of the cam. Values of u and v generated for various cam angles (θ) are plotted as coordinates against each other. The values of y and y' in equations 7a and 7b are obtained from the specified standard cam motions as listed in equations 1-4.

DEVELPEMENT OF SIMULATION SOFTWARE

Software Structure and Capability

The C/C++ high-level language was used in the development of the software codes. This language was chosen because it is well-structured and widely used in complex graphics display. It also has a powerful and varied repertoire of operations (Davies & Robotham, 1991). It is also widely used in software development. The software has the capability of generating various types of cam profiles for a selection combination (1x1x4x4) i.e. one cam type, one follower type, four follower motions, and four cam motions for the specified follower displacement profile as discussed in introduction. The software has as its outputs design details the Prime circle radius (R_o), follower face width (F_w), maximum velocity of follower (Y') max and minimum velocity of follower motions (Y') min for every cam profile designed. Thus, all the necessary parameters for the design of a chosen cam are generated by designers to accomplish different tasks.

Improved Features of Developed Software

The features of the developed software that makes it peculiar include (i) the distinct graphics demarcation of different motion segments on every generated cam profile as shown in screen shots 1-3. This makes for easy correction and re-design of the affected segments that can be easily identified. (ii) The ability to resize very large profiles and thereby make the scaled profile visible on the computer interface. These features among others makes the developed software more extensive in design analyses, synthesis and simulation based on its ability to give precise segment defects such cursps and carry out faster and more accurate re-design procedures based on graphics distinction for each segment.

Operational Sequence of Software Algorithm

The operational sequence of the arithmetic algorithm used for design calculations and profile generation based on the flow chart of the overall software algorithm in figure 2 are presented below.

1. Declaration of various header files to be used in complete software algorithm.
2. Initializations of modes for visual profile simulation display.
3. Calculations of displacements and its derivatives in the corresponding displacement- time profile for every cam profile design using equations 1a-4b.
4. Determination of minimum and maximum values of velocity, acceleration and displacement values.
5. Calculation of output design parameters such as Face width (F_w), and Prime circle radius (R_o) using equations 5 and 6.

6. The transfer of result from one part of the program to other part of the program used as input for further calculations.
7. Calculations and plotting of cam coordinate u and v for all follower and cam motion equations using equations 7a and 7b.
8. Estimation of cam profile size compared with the display screen and scaling down to fit into screen.

SAMPLE SIMULATIONS AND RESULTS.

Three sample cam profiles were simulated using the developed software. The simulations comprise of the three cam motions and follower profiles. Presented in this section are the specifications for the input design parameters for the sample simulations. The maximum follower displacement (lift) of 9.57mm and typical values of minimum radius of curvature (ρmin) between 5.00mm- 6.00mm were used in the sample simulations. Shots 1-3 show the output design screens for the sample simulations and figures 3-5 gives the motion profiles for follower displacements and their derivatives for the simulated profiles.

Sample cam profile 1

The first sample cam profile has the following specifications. (1) Follower motion: Dwell - Rise -Dwell - Return (D-R-D-R). (2) Cam motion: cycloid. (3) Cam specifications; (i) Dwell: 0^{o}-200^{o}. (ii) Rise: 200^{o} - 280^{o} (iii) Dwell: 280^{o} -300^{o}. (iv) Return: 300^{o} -360^{o}.

Sample cam profile 2

The design specifications for the second case study sample profile are as follows (1) Follower motion: Rise-Return (R-R). (2) Cam motion: Simple harmonic motion (S.H.M). (3) Cam angle specifications; (i) Rise: 0^{o}-100^{o}. (ii) Return: 100^{o} -360^{o}.

Sample cam profile 3

The fifth sample cam profile has the following specifications. (1) Follower motion: Dwell Rise -Return (R-R). (2) Cam motion: cycloid. (3) Cam specifications; (i) Rise: 0^{o} -120^{o} . (ii) Return: 120^{o} -360^{o}. Shown in table 1 are the output design parameters for the sample profiles simulated. Screen shots 1-3 also shows the output screens of the developed software for the sample designs carried out while figures 3-5 are the follower motion profiles for the simulated cams. In all the screen shots, the different cam angular segments are depicted in different colours. Screen shot (1) shows four colour demarcations for dwell-rise-dwell-return displacement profile of sample simulation 1, while screen shots 2 and 3 have two distinct colour demarcations depicting the rise-return displacement profile. Also, shown at the top right corners are the deign summaries of the profile being generated. On the top left corner are the cam angles used in the profile simulation and presented below are the output parameters used in the actual manufacture of the cam and follower components.

CONCLUSION

In this work, the tasks of designing and manufacturing planar cam-follower systems have been improved by developing a computer-aided design software package configured to generate more accurate cam profiles while reducing the long time and tedium associated with such design processes. The package has been developed from the fundamental stages of software development, namely, the use of high-level languages and software packaging techniques. The software has ability to design cam profiles for plate cams and flat face followers using the Cycloid, Simple Harmonic, Polynomial and eight- order-polynomial cam motions. The follower displacement profiles that can be handled by the software are Dwell-Rise-Dwell-Return (D-R-D-R); Rise-Return (R-R); Rise-Dwell-Return (R-D-R); Dwell-Rise-Return (D-R-R). Numerous cam angular intervals could also be specified in the software design for each the follower motions listed above. Finally the software has the additional ability to produce, as output, the cam profile or geometry, the follower face width, prime circle radius, maximum and minimum velocity of follower. All these output parameters are employed in the design and ultimately in the manufacture of the follower and the cam.

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Table 1: Design output results for simulations 1-3

Sample Simulation	Input Design Parameters		Output Design Parameters
Sample Simulation 1	Dwell	200°	Ro = 55.72 mm Fw = 33.77 mm $Y^{I}max$ = 13.71mm/rad $Y^{I}min$ = -18.28 mm/rad
	Rise	280°	
	Dwell	300°	
	Return	360°	
Sample Simulation 2	Rise	100°	Ro = 27.00 mm Fw = 13.70 mm $Y^{I}max$ = 8.61mm/rad $Y^{I}min$ = -3.31 mm/rad
	Return	360°	
Sample Simulation 3	Rise	120°	Ro = 13.72 mm Fw = 15.49 mm $Y^{I}max$ = 9.13mm/rad $Y^{I}min$ = -4.57 mm/rad
	Return	360°	

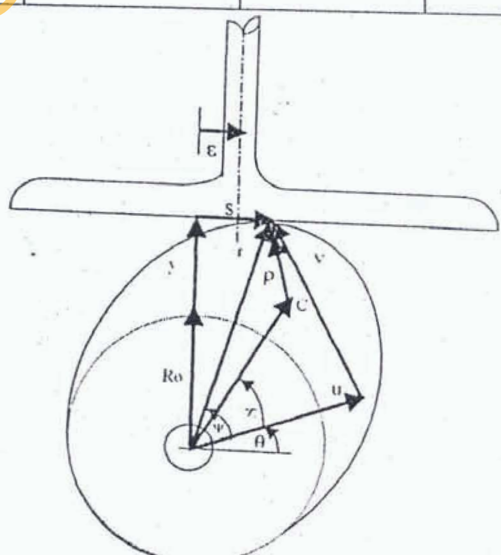

Fig. 1: Cam at point of contact with follower

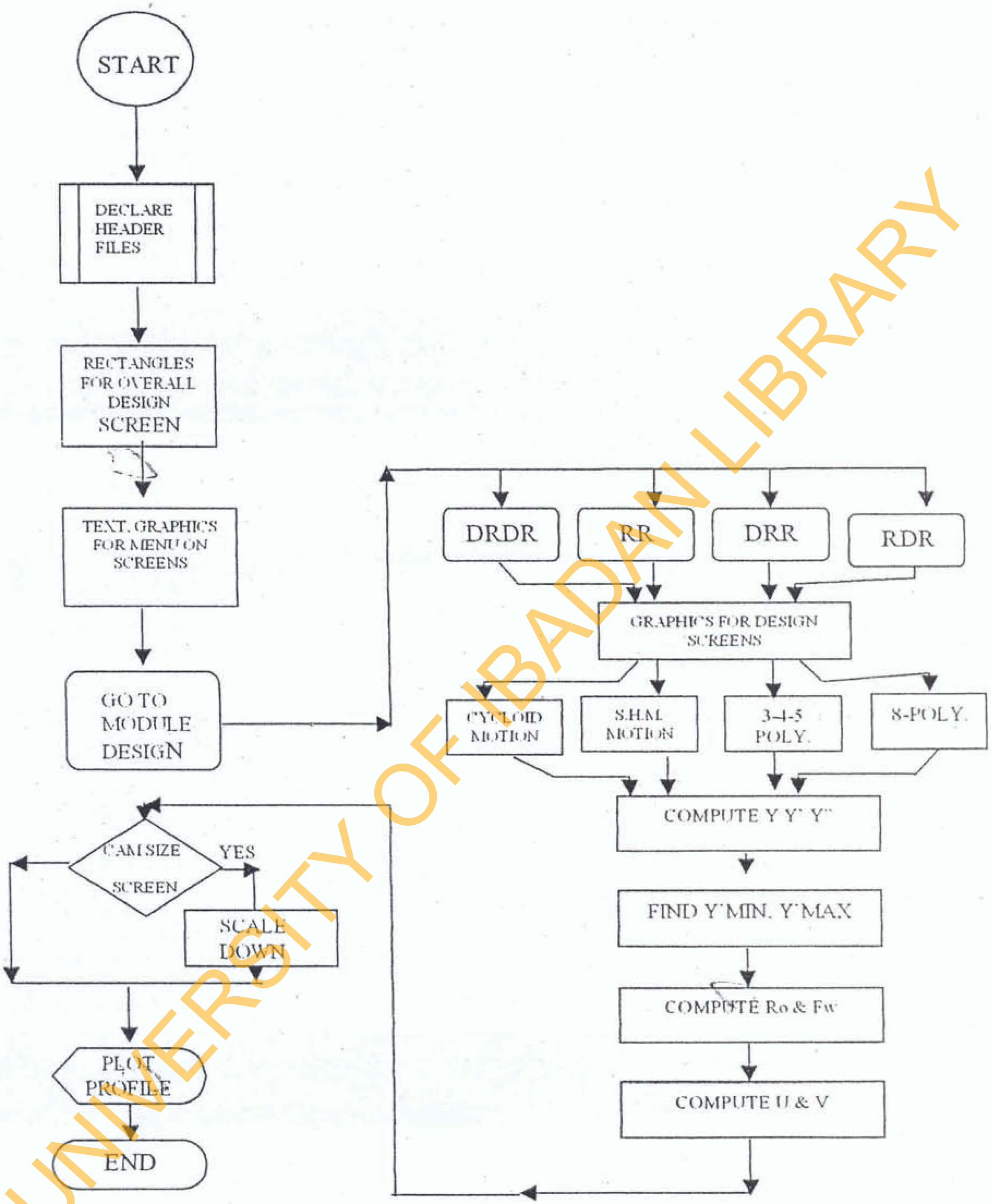

Figure2: Flow Chart of Algorithm for Developed Software