Roller-Cam Systems Design: Development of a Profile Analysis Software.

O.E. Simolowo, M.Phil.* and O.A. Bamiro, Ph.D.

Department of Mechanical Engineering, University of Ibadan, Ibadan, Nigeria.

***E-mail:** oe.simolowo@mail.ui.edu.ng

ABSTRACT

The different options involved in cam systems design such as types of cams and followers, number of applicable standard cam functions, divisions of follower motion-segments, and possible combinations of follower displacement profiles, among others, were critically studied to determine the structure and capabilities of a software package suited for extensive design analyses. The software was applied in the design of cam profiles with selected follower and cam functions and the results obtained were found comparable with those obtained from numerical methods and existing software packages.

(Keywords: cams, design, software, analyses)

INTRODUCTION

The relevance and role of cams in modern machine systems has made their continuous study necessary and inevitable. Literature searches have shown that there is a trend in the structure, usage, and design of cam systems towards better and more accurate output. Research has been carried out on almost all aspects relating to cam systems since their invention and introduction into the engineering world in the last century.

Cam systems are equivalent to four-bar mechanisms and are usually of one-degree freedom (Shigley and Uicker, 1980). They play very important roles in modern machinery and are extensively used in internal combustion engines, machine tools, printing press, packaging machines and many other applications (Norton, R. 1998; Oyawale, 2001). They provide the simplest means of achieving any desired follower motion such as found in complicated automatic operations.

The design of cam-follower systems is a process that requires highly computerized procedures to give the most optimal performance. This is because of the tedious analysis and synthesis coupled with the lengthy repetitive and multi-stage numerical procedure involved in the design. In addition, cams have been found over the years, to be hard to make compared with their design (Chen, F. 1997). Several tests have to be carried out on the cam system prior to the manufacturing stage before their final production (Owadasa, 2004). One of such tests is the profile test for discontinuity of follower motion profiles. This test involves the generation of several profiles of a particular cam (using various input design criteria) so as to see if there are discontinuities in these profiles. Synthesized cam systems with discontinuities in the profiles of higher derivatives of motion such as acceleration and jerk will result in high vibrations when used in high speed cams. Thus, the process of designing, prototyping and manufacturing a cam will naturally take a very long time if the profiles have to be generated manually during the process of profile test for discontinuity. Consequently, software packages are being developed for the design of different cam systems.

The software developed for the design of cam in this research work, like others is capable of handling various cam profiles can now be syntheses and testing within seconds during the design and manufacturing. The developed software has extended the capability of the existing packages and computer algorithms for the design analyses of different cam systems. (Yoshio T. and Sabry A. 1983; Olaniyi,1997; Udoh, 2001; Akinwole, 2004; Simolowo, 2004). The present software algorithm calculates the values of the follower displacement and its derivatives and further generates their profiles against corresponding cam angles. It also obtains critical design output parameters of roller cams. In this interactive package the user has options to select (i) follower motions, (ii) cam functions, (iii) motion segments, and (iv) cam angle increments among other parameters. Some of the unique features of the software that aids better design analysis include: (i) Increased choice of input parameters for cam design and (ii) Application of different input parameters to different cam segments in a single design among other features.

Trends in Cam Design

Cam-type motions are increasingly being used in many dynamic systems to move loads with smooth starts and stops (Gupta and Wiederrich, 1986). They make the attainment of almost any desired follower motion possible (Oyawale, 2001). From the standpoint of engineering application cams have the following advantages over fundamental kinematics four-bar linkages that are used for similar purposes.

(1) Their designs are better understood, and with the application of recent CAD procedures, are made easier and faster.
(2) The actions they produce are most accurate to forecast.
(3) They produce desired complicated motions that are difficult for linkages, such as causing the follower system to remain stationary during a portion of a cycle.
(4) They occupy less space when compared with linkage systems

Changes have taken place generally in all aspects of cam systems since their application in various areas of machinery design. However, the most prominent and relevant to this research work are those trends in the area of their design. Various methods have been applied over the years in the design of cam systems so as to give the best design in terms of calculating critical output parameters and generation of cam and motion profiles. One of the earliest methods used in the generation of cam profiles was the use of graphical layout method (Jensen, 1968; Shigley and Uicker, 1980). This method entailed the transfer of distances from the displacement diagram of the follower onto the cam drawing so as to generate the cam profile. The method however, had the problem of undercutting (inability to produce a complete cam profile without sharp edges).

Various mathematical methods have also been applied to cam systems in an attempt to find the best way of designing the components. On the modification of cam-type profiles, a procedure derived from the convolution theorem for Fourier transforms was used to systematically modify cam-type profiles which accomplished the dual task of smoothing starts and stops, as well as improving its residual vibration characteristics (Gupta and Wiederrich, 1986). Also, the Regular-Falsi and Newton-Raphson of iterative numerical solution of nonlinear equations are among the mathematical methods that have been used in the optimum design of plate cam size avoiding undercutting (Yoshio and Sabry, 1983).

In recent times the trend in cam design is towards producing better motion requirements for high-speed applications. To this end, equations for a number of standard types of displacement curves that can be used to address most high-speed cam motion requirements have been considered. These equations include those for trigonometric and polynomial functions among others. The common approach in this method of design is to synthesize appropriate motion curves with these standard equations.

PRESENTATION OF DESIGN PARAMETERS FOR ROLLER CAMS

In this section the design input (required) and output (calculated) parameters and their equations are presented as shown in Figure 1. The input parameters are:

1. Cam/follower pressure angle (ϕ)
2. The roller radius R_r.
3. The prime circle radius (R_o)
4. The eccentricity (Є)

The output parameters include:

1. The roller cam coordinates (u, v).
2. The radius of curvature of cam profile (ρ)
3. The radius of curvature of pitch circle (ρ_{pitch})
4. The follower displacement and derivatives (y, y' and y")

Cam/Follower Pressure Angle

An expression for pressure angle is given in Equation (1) (Shigley, 1980):

$$\phi = \tan^{-1}((y' - \epsilon)/ ((R_o^2 - \epsilon^2)^{1/2} + y)) \qquad \textbf{(1)}$$

From (1) it can be seen that once the displacement equations y are known R_o and ε can be adjusted to get an appropriate pressure angle ϕ. Pressure angle ϕ is continuously changing with the rotation of the cam and therefore we require the extreme values of ϕ.

Minimum Radius Of Curvature and Cam Coordinates

To calculate the radius of curvature of the cam profile (ρ), the radius of curvature of the pitch curve (ρ_{pitch}) equation is given by:

$$\rho_{pitch} = \rho + R_r = \frac{\left[(R_o + y)^2 + (y')^2\right]^{3/2}}{(R_o + y)^2 + 2(y')^2 - (R_o + y)y''} \quad \textbf{(2)}$$

is used. The rectangular coordinates (u, v) of the cam profile of plate cam with a reciprocating roller follower are given by:

$$u = \left(\sqrt{R_o - \varepsilon^2} + y\right)\sin\theta + \varepsilon\cos + R_r\sin(\phi - \theta) \quad \textbf{(3a)}$$

$$v = \left(\sqrt{R_o - \varepsilon^2} + y\right)\sin\theta - \varepsilon\cos - R_r\sin(\phi - \theta) \quad \textbf{(3b)}$$

Cam Functions and Follower Motions

Where ϕ is the pressure angle given by Equation (1) (Shiegley, 1980). The cam functions are expressed in terms of the follower displacements and their derivatives. The cycloid and modified harmonic are presented later in Equations (5a) – (6f).

SOFTWARE ARCHITECTURE

The software structure and features enhancing comprehensive and extensive cam design analyses for plate cams with roller followers carried out in this work are here by presented in this section.

Features of Developed Software

The peculiar features of the developed software compared with features of widely used software include the following:

1. Possibility of using a wider range of angular increments in design simulation and analysis of all follower and cam profiles generated as compared with a maximum of few possible increments in existing packages.
2. Application of different angular increment to different cam segment in a single simulation for every profile generated. Examples of this feature are shown in screenshots 2, 3 and 4 below. Existing packages apply only same angular increment to all the motion segments in a single cam design.
3. Application of different roller radii in segment-by-segment simulation of cam profile as shown in screen shot 5. In existing packages, only a specified roller radius is used for all the motion segments in a particular simulation.
4. Presentation of motion derivatives results in both linear and radial dimensions. Other packages consider either linear or radial dimensions in their result output.
5. Distinct graphics demarcation of different motion segments on every cam profile generated as shown in screen shots 2, 3, 4, and 5. This makes for easy correction and re-design of the affected segments that can be easily identified.
6. Simplified and less cumbersome designs on increased interfaces.

These features among others make the developed software more extensive in design analyses, synthesis and simulation based on the following reasons.

1. More cam profiles can be generated by the software because of the increased choice of cam angle increments.
2. Different design analyses are possible for various segments of a cam profile within a single simulation based on its ability to apply different increments and roller radii in these segments.
3. Ability to give precise segment of design defects such as cursps and carry out faster and more accurate re-design procedures based on graphics (color) distinction for each segments.

4. Its universality in design simulation applications due to its ability to handle both linear and radial displacement derivatives.

Software Structure and Interface

Software for design analyses of roller cam systems has been designed in this work. This developed software is suitable for extensive cams design analyses. The developed algorithm using an object-oriented high level language (Byron S, 2004; Evangelos, P, 2002) was based on numerical procedures obtained from the literature. The software structure consists of five different program modules. They are:

(1) Declaration of program statements and variables
(2) Selection of design options
(3) Generation of follower motion values, design output parameters and cam coordinates.
(4) Generations of Cam and follower profile
(5) Description of subprogram and public functions called in modules 2 - 4 above.

The software interface development for the overall software is based on the overall cam design option chart of the developed software shown in Figure 2. The figure is a representative diagram of the designed active screens common to the roller follower options for the software. The screens are in three parts. (i) Input screens (1-4); (ii) Tutor screens (5-7); (iii) Result output screens (8-15).

Sequence of Algorithm Operations

The sequence of operations of the developed algorithm is presented below.

1. The following input parameters are read into the computer; prime circle radius R_o, roller radius R_r and eccentricity ε based on the design criteria

2. For specified cam angle intervals within each motion segment; the algorithm calculates the following:

(i) The follower displacement and derivatives y' and y" using the equations of the required cam function.
(ii) The pressure angle ϕ using equation (1). The ϕ_{max} and ϕ_{min} for each segment. ϕ_{max} must not exceed 30 to 35°.
(iii) Radius of curvature of cam profile ρ using equation (2) and the minimum value ρ_{min} for that segment
(iv) The values of cam coordinates u and v using equations (3a and 3b) respectively.

3. The overall ϕ_{max}, ϕ_{min} and ρ_{min} from all the ϕ_{max}, ϕ_{min} and ρ_{min} of the different segments considered in the design are calculated.

4. The ρ_{pitch} using overall ρ_{min} and equation (2) is also computed.

Software Procedure for Determining R_o with $\phi_{Max} > 35^o$

In the design of plate cams using roller follower, the values of ϕ_{max} must be checked so as not to exceed 30 to 35° in each of the follower motion segments. For cases with ϕ_{max} exceeding these values in one or more of the segments, the sequence of operation of the algorithm is described below.

1. The values of maximum pressure angle Φ (30-35°) for each of the motion segments are read as input values.

2. In each of the follower motion segments, with the given Lift L, Cam angular difference β, initial and final angles of cam rotation, the algorithm calculates the following;

(i) y' and y" for each increment in cam angle using the equations of the required cam functions.
(ii) R_o : making R_o the subject of the formula given in equation (1) to arrive at:

$$R_o = \sqrt{\left(\left(\frac{y'-\varepsilon}{\tan\phi}\right) - y\right)^2 + \varepsilon} \qquad \textbf{(4)}$$

3. The overall maximum values of the prime circle radius R_o from all the calculated values in the different follower motion segments are determined.

Once the new value of prime circle radius R_o is determined following the steps described above, a complete re-design is carried out for the motion segments using the newly calculated prime circle radius R_o.

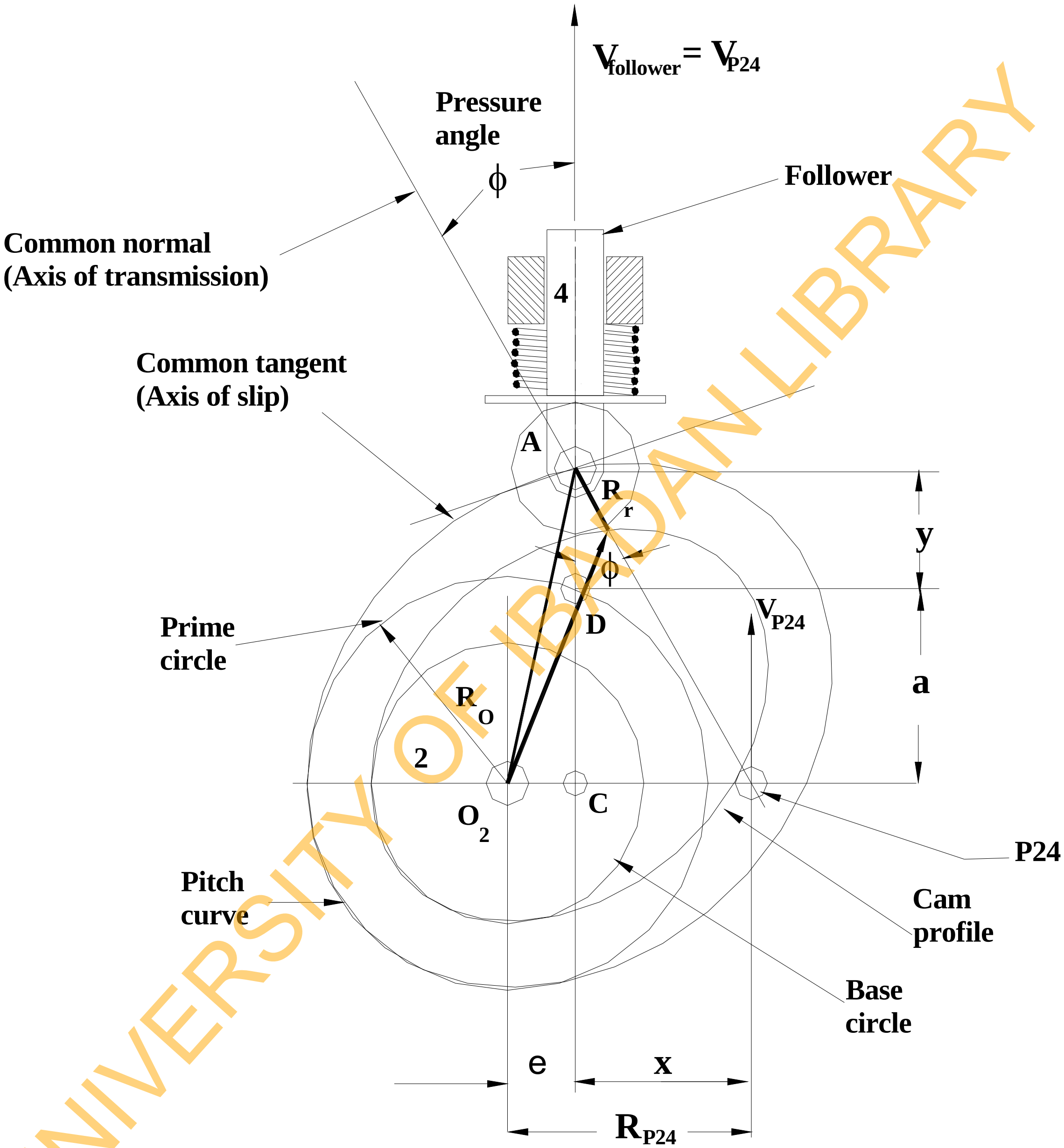


Figure 1: Plate Cam in Contact with Reciprocating Roller Follower

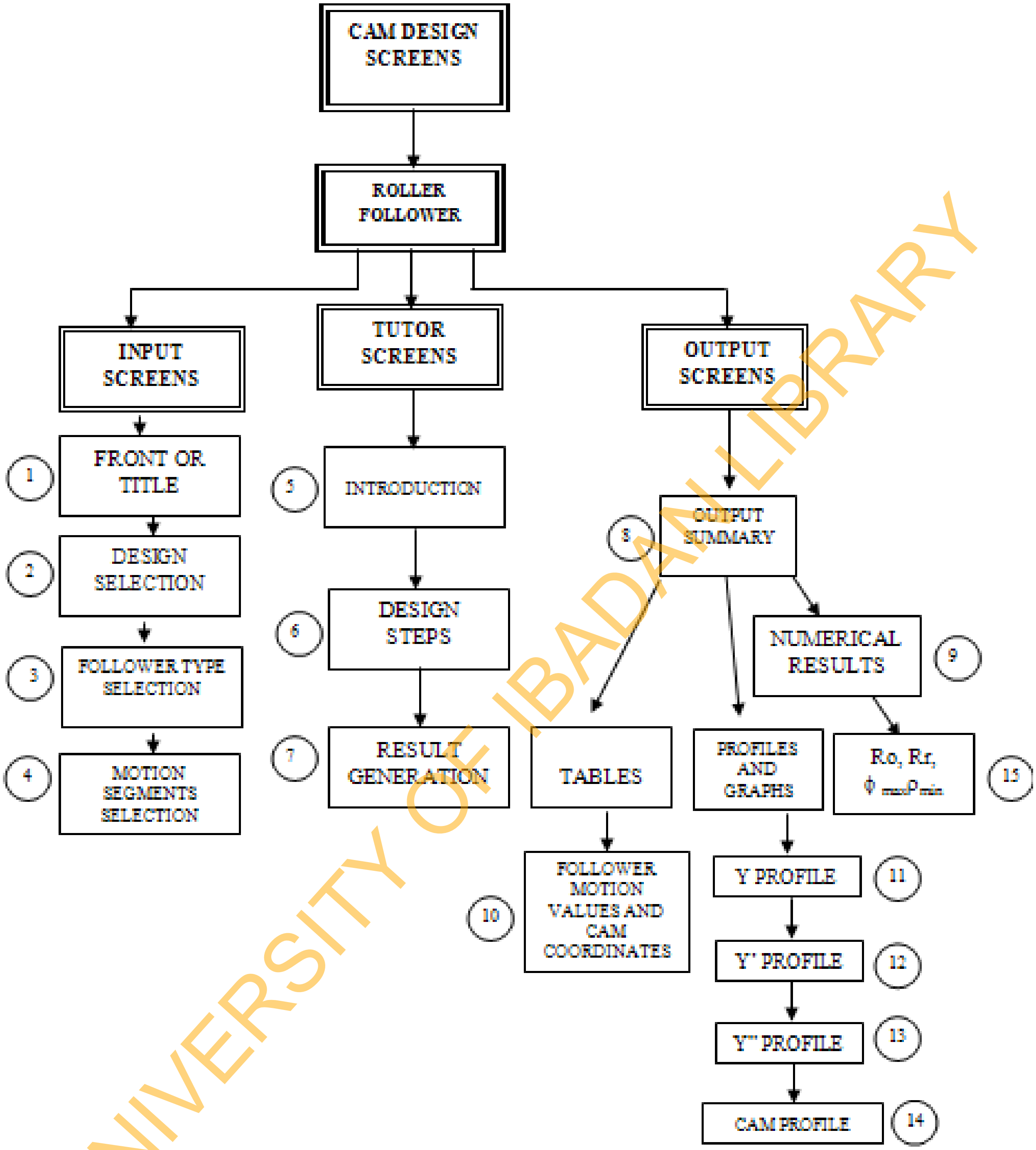


Figure 3: Representation of Display Screens for the Developed Software.

SOFTWARE RESULTS VALIDATION AND APPLICATION

Validation Methodology

In the validation of the software using numerical results, the procedures presented earlier for the numerical and software design of roller cam systems were adhered to. Three critical design parameters as presented by Shigley and Uicker, (1980) were used in the results validation Viz. determination of (i) minimum prime circle radius R_o (ii) maximum pressure angle ϕ_{max} (iii) minimum radius of cam curvature $\rho_{min.}$ The values of y, y', y'' of the cycloid and Modified harmonic motions employed in the result validation were obtained from Equations (5a & 5b) and (6a – 6f), respectively. Four different design case studies were used in the validation. The first case study involved the computation of the prime circle radius R_o for a cycloid rise motion while the second and third design cases considered the calculation of maximum pressure angles ϕ_{max} for modified harmonic and cycloid motion respectively. The minimum radius of curvature was determined using the numerical and software procedures for a cycloid-rise motion in the fourth case. Shown in Table 1 are the input parameters for the design cases considered in the software validation. θ_1 and θ_2 are the angles specifying the range of the motion segment being considered.

Cycloid – Rise Motion

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

$$y' = \frac{L}{\beta}\left(1 - \cos\frac{2\pi\theta}{\beta}\right) \qquad \textbf{(5a)}$$

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

$$y''' = 4\pi^2\frac{L}{\beta^3}\cos\left(2\pi\frac{\theta}{\beta}\right)$$

Cycloid – Return Motion

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

$$y' = -\frac{L}{\beta}\left(1 - \cos\frac{2\pi\theta}{\beta}\right) \qquad \textbf{(5b)}$$

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

$$y''' = -4\pi^2\frac{L}{\beta^3}\cos\left(2\pi\frac{\theta}{\beta}\right)$$

Modified Harmonic Rise-Motion:

For $0 \le \theta \le \frac{1}{8}\beta$

$$y = L\left[0.43990085\frac{\theta}{\beta} - Z1\right]$$

Where $Z1 = \left[0.0350062\sin\left(4\pi\frac{\theta}{\beta}\right)\right]$

$$y' = 0.43990085\frac{L}{\beta}\left[1 - \cos\left(4\pi\frac{\theta}{\beta}\right)\right]$$

$$y'' = 5.5279571\frac{L}{\beta^2}\sin\left(4\pi\frac{\theta}{\beta}\right) \qquad \textbf{(6a)}$$

$$y''' = 69.4663577\frac{L}{\beta^3}\cos\left(4\pi\frac{\theta}{\beta}\right)$$

For $\frac{1}{8}\beta \le \theta \le \frac{7}{8}\beta$,

$$y = L\left[0.28004957 + 0.43990085\frac{\theta}{\beta} - Z2\right]$$

Where $Z2 = \left[0.31505577\cos\left(\frac{4\pi}{3}\frac{\theta}{\beta} - \frac{\pi}{6}\right)\right]$

$$y' = 0.43990085\frac{L}{\beta}\left[1 + 3\sin\left(\frac{4\pi}{3}\frac{\theta}{\beta} - \frac{\pi}{6}\right)\right] \qquad \textbf{(6b)}$$

$$y'' = 5.5279571\frac{L}{\beta^2}\cos\left(\frac{4\pi}{3}\frac{\theta}{\beta}-\frac{\pi}{6}\right)$$

$$y''' = -23.1553\frac{L}{\beta^3}\sin\left(\frac{4\pi}{3}\frac{\theta}{\beta}-\frac{\pi}{6}\right)$$

For $\frac{7}{8}\beta \le \theta \le \beta$ **,**

$$y = L\left\{0.56009915 + 0.43990085\frac{\theta}{\beta} - Z3\right\}$$

$$Z3 = \left\{0.0350062\sin\left[2\pi\left(2\frac{\theta}{\beta}-1\right)\right]\right\}$$

$$y' = 0.43990085\frac{L}{\beta}\left\{1-\cos\left[2\pi\left(2\frac{\theta}{\beta}-1\right)\right]\right\}$$

$$y'' = 5.5279571\frac{L}{\beta^2}\sin\left[2\pi\left(2\frac{\theta}{\beta}-1\right)\right] \qquad \textbf{(6c)}$$

$$y''' = 69.4663577\frac{L}{\beta^3}\cos\left[2\pi\left(2\frac{\theta}{\beta}-1\right)\right]$$

Modified Harmonic Return-Motion:

For $0 \le \theta \le \frac{1}{8}\beta$ **,**

$$y = L\left[1\text{-}0.43990085\frac{\theta}{\beta} - Z4\right]$$

Where $Z4 = \left[0.0350062\sin\left(4\pi\frac{\theta}{\beta}\right)\right]$

$$y' = -0.43990085\frac{L}{\beta}\left[1-\cos\left(4\pi\frac{\theta}{\beta}\right)\right] \qquad \textbf{(6d)}$$

$$y''' = -69.4663577\frac{L}{\beta^3}\cos\left(4\pi\frac{\theta}{\beta}\right)$$

$$y'' = -5.5279571\frac{L}{\beta^2}\sin\left(4\pi\frac{\theta}{\beta}\right)$$

For $\frac{1}{8}\beta \le \theta \le \frac{7}{8}\beta$ **,**

$$y = L\left[1\text{-}0.28004957 + 0.43990085\frac{\theta}{\beta} - Z5\right]$$

Where $Z5 = \left[0.31505577\cos\left(\frac{4\pi}{3}\frac{\theta}{\beta}-\frac{\pi}{6}\right)\right]$

$$y' = -0.43990085\frac{L}{\beta}\left[1+3\sin\left(\frac{4\pi}{3}\frac{\theta}{\beta}-\frac{\pi}{6}\right)\right]$$

$$y'' = -5.5279571\frac{L}{\beta^2}\cos\left(\frac{4\pi}{3}\frac{\theta}{\beta}-\frac{\pi}{6}\right) \qquad \textbf{(6e)}$$

$$y''' = 23.1553\frac{L}{\beta^3}\sin\left(\frac{4\pi}{3}\frac{\theta}{\beta}-\frac{\pi}{6}\right)$$

For $\frac{7}{8}\beta \le \theta \le \beta$ **,**

$$y = L\left\{1\text{-}0.56009915 + 0.43990085\frac{\theta}{\beta} - Z6\right\}$$

Where $Z6 = \left\{0.0350062\sin\left[2\pi\left(2\frac{\theta}{\beta}-1\right)\right]\right\}$

$$y' = -0.43990085\frac{L}{\beta}\left\{1-\cos\left[2\pi\left(2\frac{\theta}{\beta}-1\right)\right]\right\}$$

$$y'' = -5.5279571\frac{L}{\beta^2}\sin\left[2\pi\left(2\frac{\theta}{\beta}-1\right)\right]$$

(6f)

$$y''' = -69.4663577\frac{L}{\beta^3}\cos\left[2\pi\left(2\frac{\theta}{\beta}-1\right)\right]$$

Software Application

The developed software was used to carry out sample simulation of 2, 3, 4, 6, and 7 motion segments for the roller follower design option. The final motion and cam profiles are presented in screenshots 1, 2, 3, 4, and 5, respectively. The simulations also show some of the improved features of the software as discussed earlier

Simulation Results

Figures 2, 3, 4, and 5 show that all the results obtained from the two methods (software and numerical) are within the same ranges. The choice of cam motions for the case study designs considered in the validation of research results have been limited to existing data in literatures. They are the Cycloid (half and full) and the Modified Harmonic motions. The Full cycloid and M. Harmonic have been taken into consideration since the software can handle these design options.

Table 1: Input Parameters for Software Validation Case Studies.

DESIGN CASES	(1)	(2)	(3)	(4)	(5)
θ_1 (DEG)	0	163.5	0	163.5	163.5
θ_2 (DEG)	182	300	182	300	300
β (DEG)	182	136.5	182	136.5	136.5
L (MM)	64.26	76.20	64.26	76.20	76.20
ϕ (DEG)	30	30	+	+	+
R_O (MM)	+	+	82.5	82.5	82.5
R_R (MM)	+	+	+	+	12.7
CAM MOTION	CYCLOID	M. HARMONIC	CYCLOID	M. HARMONIC	CYCLOID
FOLL. MOTION	RISE	RETURN	RISE	RETURN	RISE
+THESE VALUES ARE NOT NEEDED AS INPUT FOR INDICATED DESIGN CASE STUDY					

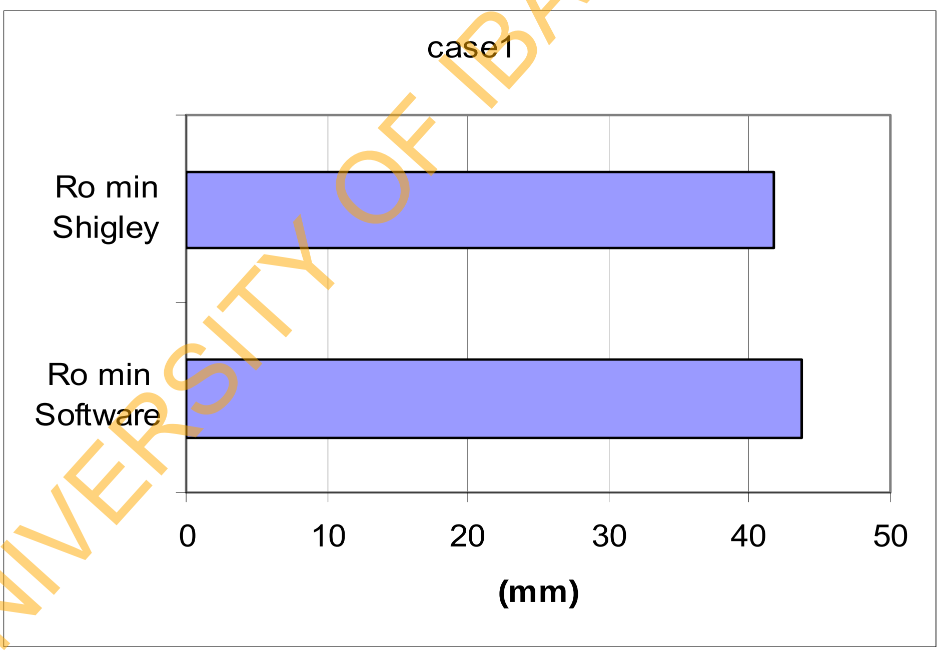


Figure 2: Numerical Results (Shigley and Uicker) vs. Software Results for Design Case 1.

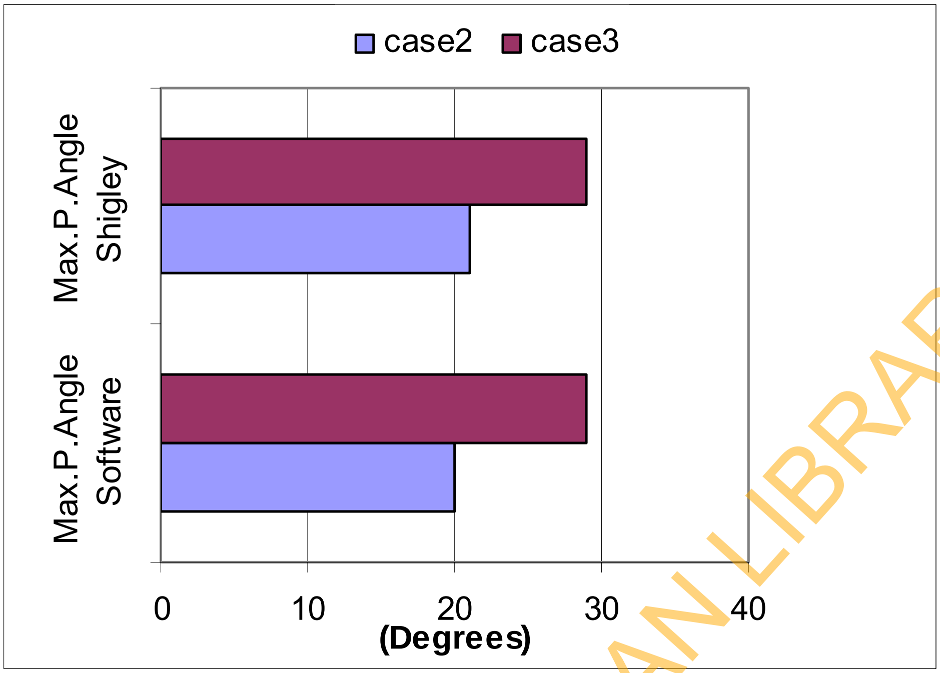


Figure 3: Numerical Results (Shigley and Uicker) vs. Software Results for Design Cases 2 and 3.

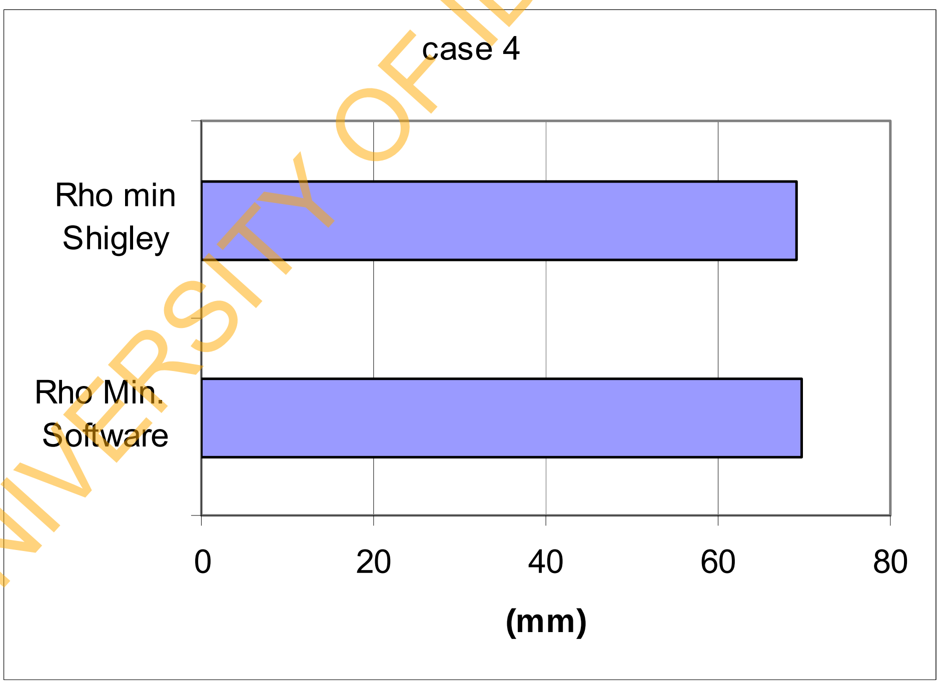


Figure 4: Numerical Results (Shigley and Uicker) vs. Software Results for Design Case 4.

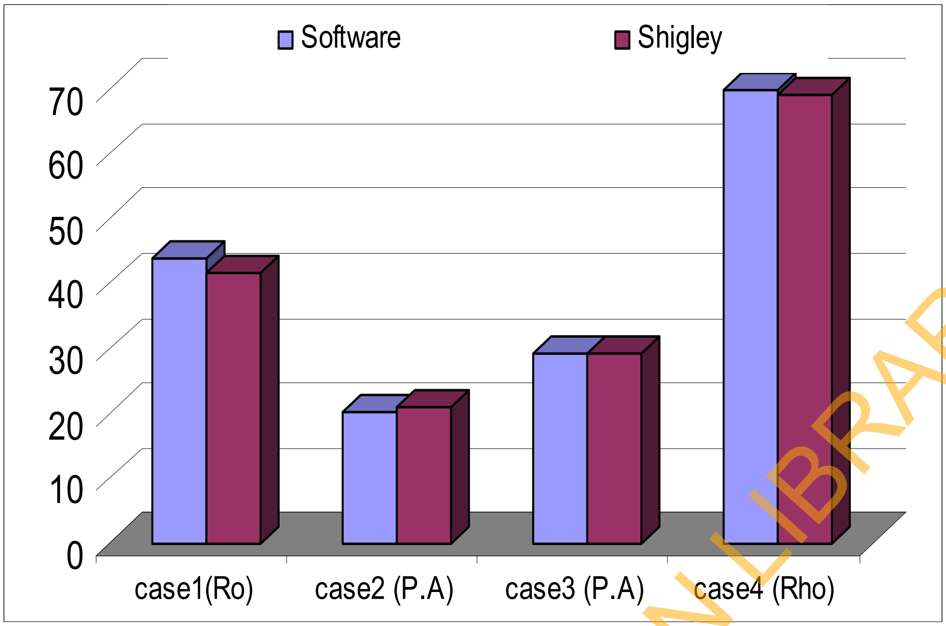
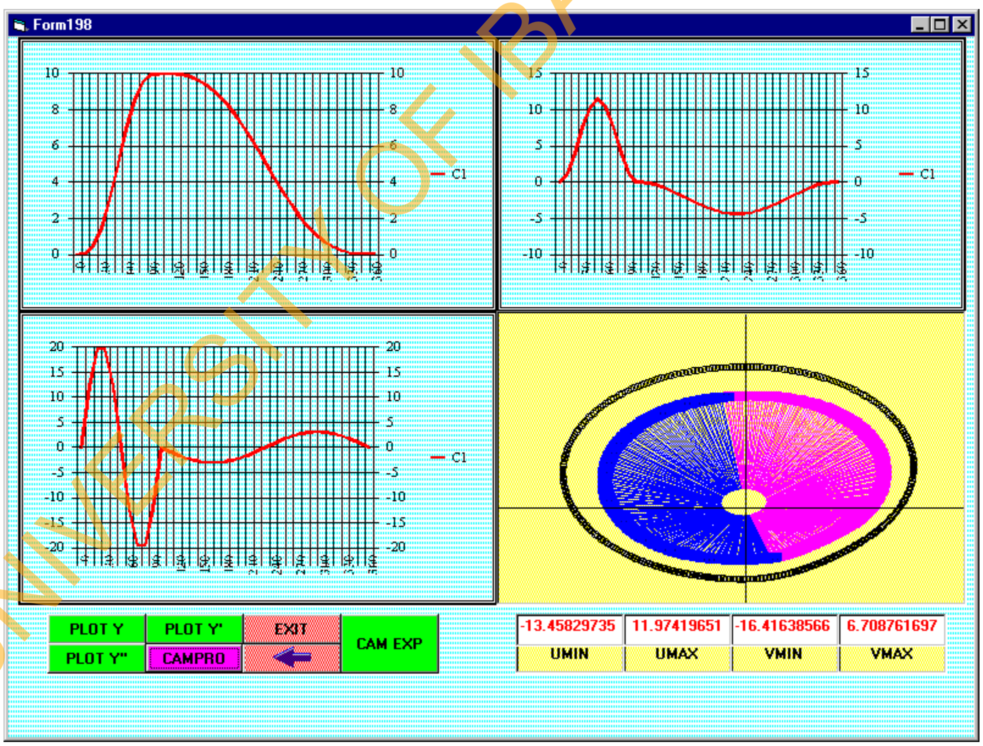


Figure 5: Combined Numerical Results (Shigley and Uicker) vs. Software Results for All Cases.



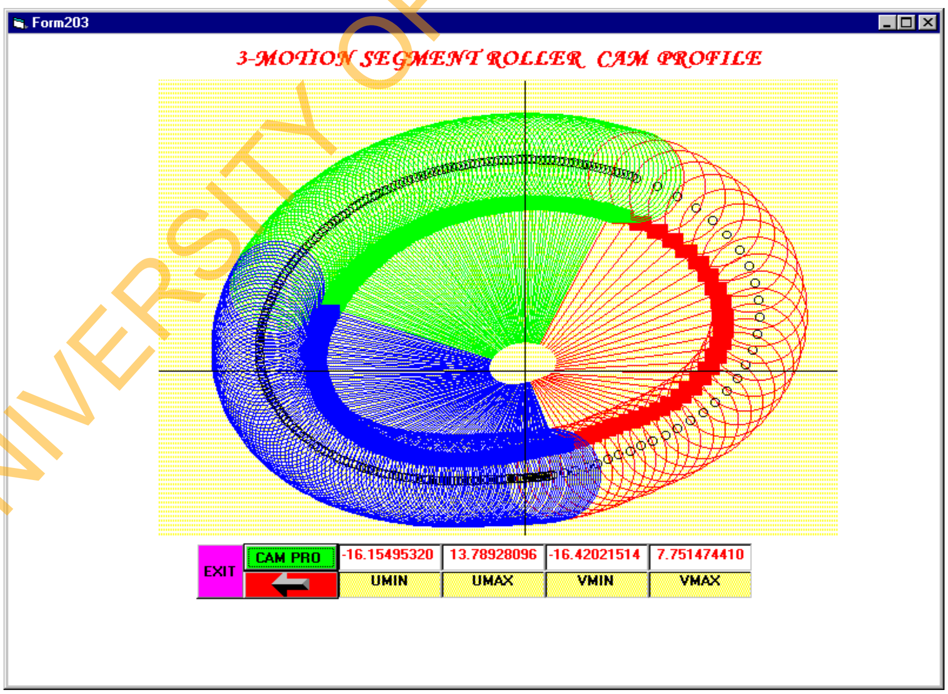
Screenshot 1: Display of Y, Y', Y" and cam Profile for 2-segmented Motion (Roller follower) on a Single Interface.

Shown in screen shot 1 is the combination of the displacement profile and its derivatives for a 2-motion segment (Rise- Return) simulation carried out by the software. Screen shot 2 shows a roller cam profile for 3-motion displacement profile. It also shows the application of two different angular increments in the generation of the cam profile. In screen shot 3, simulation is carried out for a 4-motion displacement. Also, different degree increments have been applied to the four different segments. In screen shot 4, the segment-by-segment application of the increased cam angle increment in the generation of a 6-motion segment cam profile is shown. Screen shot 5 is a design output showing a 7-motion segment cam profile with different roller radii simulated over the different motion segments.

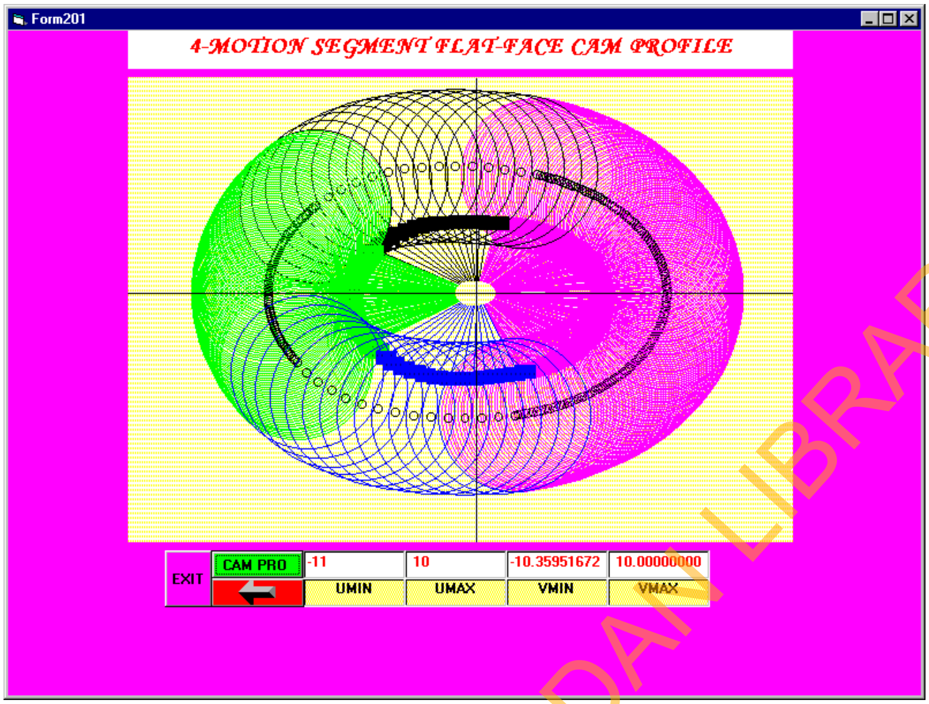
CONCLUSION

Software algorithms that can be used for more comprehensive deign analysis of plate cam systems with reciprocating roller follower has been developed. The many design combinations, repetition of calculations coupled with plotting of hundreds of cam and follower profile points involved in cam systems design has justified the need for the continuous development of various software in this area. The software design algorithm entailed the use of standard trigonometric and polynomial cam functions in simulating the follower motion derivatives; determining the follower and cam design parameters; generating the cam coordinates; and finally drawing the follower motions and cam profiles.

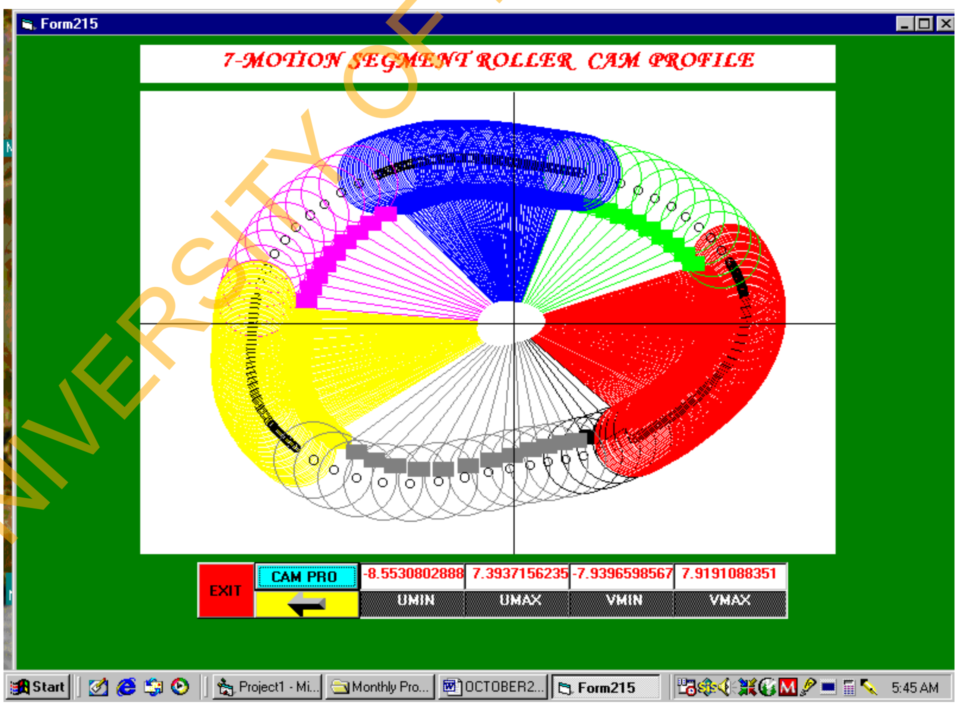
Among some of the features of the developed software, there are some unique ones. They include; increased angular increment in generating all the cam and follower profiles and in calculating all design parameters; segment by segment application of the increased angular increment in generating cam and follower profiles and determination of other values; presentation of design results to include the rotational and linear dimensions for all follower motions and its derivatives. Using it to simulate cam systems with various follower motion requirements validated the software. The results obtained conformed to those of other related works for the same set of follower motion requirements.



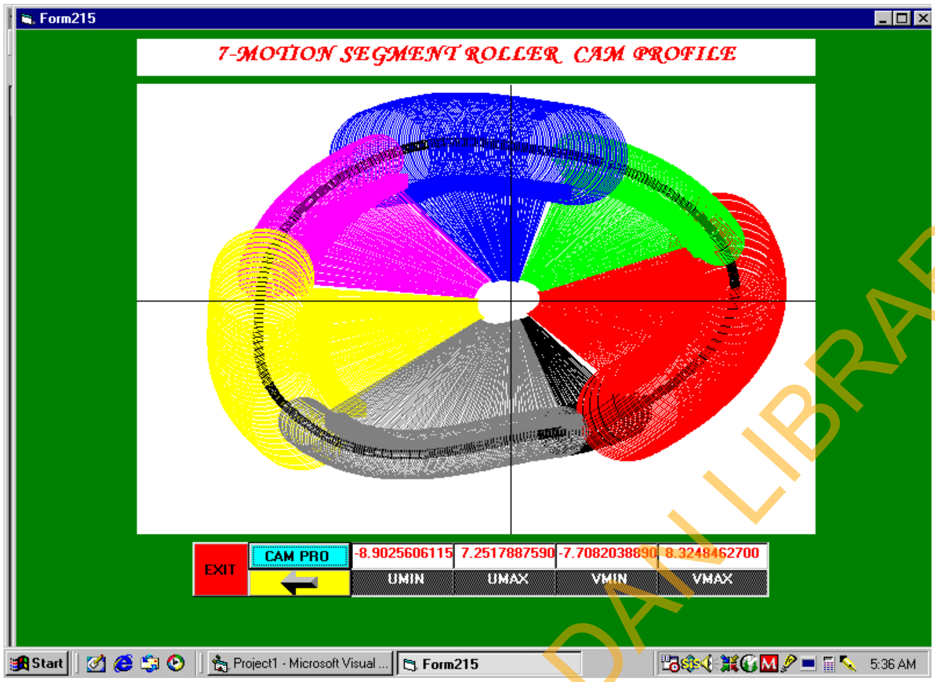
Screenshot 2: Cam Profile Simulation using Different Degree Increments and Same Roller Radius for Three Motion Segments.



Screenshot 3: Cam Profile Simulation using Different Degree Increments and Same Roller Radius for Four Motion Segments.



Screenshot 4: Cam Profile Simulation using Different Degree Increments and Same Roller Radius for Six Motion Segments.



Screenshot 5: Cam Profile Simulation using Different Roller Radius for Seven Motion Segments.

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ABOUT THE AUTHORS

O. E. Simolowo lectures at the Department of Mechanical Engineering, University of Ibadan in Nigeria. He holds a Masters of Philosophy degree in Mechanical Engineering from the same institution. He is a corporate member of the Nigerian Society of Engineers and a Registered Engineer of the Council for the Regulation of Engineering in Nigeria. His areas of research and specialization are Machine Design, Engineering Software Development, and Solid Mechanics of which he has publications in learned journals.

O. A. Bamiro is a professor of Solid Mechanics at the Department of Mechanical Engineering University Of Ibadan, Nigeria. He obtained his B.Sc. degree in Mechanical Engineering from Nottingham University, England and Doctor of Philosophy degree at the McGill University, Montreal, Canada. He is a fellow of the Nigerian Society of Engineers and also Fellow of the Academy of Science in Nigeria. He has published widely in his research areas which include Systems Dynamics, Engineering and Strategic Planning Software Development in the area of management decision making. He is currently the Vice-Chancellor of the University of Ibadan. Nigeria.

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