Formulation of Standard Design Procedure for Automatic Generation of Disc Cam Profile in a Diesel Engine Application Using PTC Mathcad

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Abstract - The aim of this study is to formulate standard design procedure for automatic generation of disc cam profile for camshaft in single cylinder four stroke diesel engine using PTC Mathcad. The study focused on mainly single cylinder four stroke diesel engines. Calculations are carried out to formulate standard design procedure for disc cam and to understand its relationship with other operating parameters. Analytical calculations are highly complex and very difficult to perform using Microsoft Excel worksheet. So that, Mathcad can be extensively use for this type of complex calculations and formulations. Standard design procedure created using Mathcad calculates various changes in design parameters and modifies CAD model automatically. Mathcad has unique capability of assigning units for calculation notes in which Microsoft Excel lack behind. After performing whole calculations, the procedure is integrated with actual CAD model of the disc cam whose sketch is generated automatically using Mathcad. The requirements on the roller radius for the rolling motion of the roller relative to the cam contour are analysed. Camshaft lobe profile generation is very tedious and time consuming process in CAD. This process can be simplified to great extent by using methodology described in this paper.

Keywords: Cam contour, Movement law, Radius of roller, Formulation using Mathcad, Procedure of integration between Creo and Mathcad.

I. INTRODUCTION

The objective of the study is to formulate standard design procedure for disc cam in single cylinder four stroke diesel engine using PTC Mathcad. Profile for disc cam is generated by using automatic formulation by Mathcad. Detail procedure opted for integration gives automatic modification of CAD model. This design template can be applied to many other disc cam design for various engines. This formulated design act as building block for certain disc cam application at starting of design.

II. DISC CAM WITH ROLLER FOLLOWER

The requirements on the movement law of the follower imposed by disc cam mechanism of roller follower and the influencing factors of the relative motion between the roller and the cam contour are considered. The requirements of the roller radius for the rolling motion of the roller that is relative to the cam contour are analyzed. It can be found that the fixed value movement speed, one of the follower motion law, cannot be applied only to roller follower disc cam mechanism; otherwise movement distortion for the follower will occur. [1]

The cause of movement distortion is inappropriate choice of movement law cannot be avoided by increasing cam base circle radius or by decreasing roller radius. There should be minimum roller radius for the relative movement between the roller and cam contour. This radius is inversely related to the rolling friction coefficient between roller and cam contour is directly proportional to the radius of the friction circle of the revolute pair between roller and follower lever. [1]

A cam is a rotating or sliding piece in a mechanical linkage used especially in transforming rotary motion into linear motion. It is often a part of a rotating wheel or shaft that strikes a lever at one or more points on its circular movement path. [1]

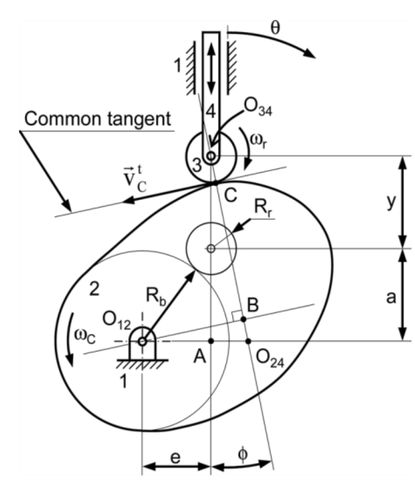


Fig. 2.1 Disc cam with roller follower. [1]

III. PREVIOUS WORK

The geometry of the modelled cam component in PTC Creo has been adopted from a study originally performed by Matt Heinloo, Eino Aarend and Heiki Anton of the Estonian Agricultural University. [1]

IV. MATHCAD METHODOLOGY

The section discuss the methodology used to create the design procedure for the Disc cam using Mathcad software. The design procedure for design of disc cam with roller follower consists of following steps:

Consider,

- Φ_r = Rise angle of the follower in radians.
- Φ_d = High dwell angle of the follower in radians.
- Φ_f = Fall angle of the follower in radians.
- Φ_{ld} = Low dwell angle of the follower in radians.
- H = Stroke of the follower in mm.
- R_0 = Radius of the cam base circle, to centre of follower in mm.
- Φ_p = Minimum value of pressure angle in deg.
- N = Number of positions of cam in computations.
- ε = Offset of the follower in mm.
- r_r = Radius of the roller in mm.

Low dwell angle of the follower is given by –

$$\phi_{ld} := 360\ deg - \phi_r - \phi_d - \phi_f$$

Laws of acceleration profiles of the follower for rise period are –

$$a_1(\psi) := \frac{2 \cdot H \cdot \pi}{\phi_r^2} \cdot \sin\left(\frac{2 \cdot \pi}{\phi_r} \cdot \psi\right)$$

…….. (Sine law)

$$a_1(\psi) := \frac{H \cdot \pi^2}{2 \cdot \phi_r^2} \cdot \cos\left(\frac{\pi}{\phi_r} \cdot \psi\right) \cdot \frac{1}{s^2}$$

…….. (Cosine law)

$$a_1(\psi) := \frac{G \cdot H}{\phi_r^2} \cdot \left(1 - \frac{2 \cdot \psi}{\phi_r}\right)$$

…….. (Linear law)

Here cosine law is used for acceleration profile of the follower for rise period.

Laws of acceleration profiles of the follower for fall period are –

$$a_2(\psi) := -\frac{2 \cdot H \cdot \pi}{\phi_f^2} \cdot \sin\left(\frac{2 \cdot \pi}{\phi_f} \cdot (\psi - \phi_r - \phi_d)\right)$$

……. (Sine law)

$$a_2(\psi) := -\frac{H \cdot \pi^2}{2 \cdot \phi_f^2} \cdot \cos\left(\frac{\pi}{\phi_f} \cdot (\psi - \phi_r - \phi_d)\right) \cdot \frac{1}{s^2}$$

…….. (Cosine law)

$$a_2(\psi) := -\frac{G \cdot H}{\phi_f^2} \cdot \left(1 - \frac{2 \cdot (\psi - \phi_r - \phi_d)}{\phi_f}\right)$$

…….. (Linear law)

Here cosine law is used for acceleration profile of the follower for fall period.

Using the cosine law mention above, the profile for acceleration throughout one complete cycle of cam's motion can be determined by the following logic –

$$a(\psi) := \mathbf{if}\,(0 < \psi, a_1(\psi), 0)$$

$$a(\psi) := \mathbf{if}\,(\phi_r \le \psi, 0, a(\psi))$$

$$a(\psi) := \mathbf{if}\,(\phi_r + \phi_d \le \psi, a_2(\psi), a_1(\psi))$$

$$a(\psi) := \mathbf{if}\,(\phi_r + \phi_d + \phi_f \le \psi, 0, a_2(\psi))$$

Through the profile of the curve, using the number of points from the beginning as –

$$i := 0..N$$

$$\psi_i := \frac{2 \cdot \pi}{N} \cdot i$$

For determination of the velocity profile we define the following functions –

$$v_1(\psi) := \int_{0.001}^{\psi} a_1(x)\,dx$$

$$v_2(\psi) := \int_{\phi_r + \phi_d}^{\psi} a_2(x)\,dx$$

And compute

$$v1_i := v_1(\psi_i) \cdot s$$

$$v2_i := v_2(\psi_i) \cdot s$$

The velocity profile for one cycle of cam's motion can be determined by the following logic –

$$v_i := \mathbf{if}\left(0 \le \psi_i, v1_i, 0\ \frac{m}{s}\right)$$

$$v_i := \mathbf{if}\left(0 \le \psi_i, 0\ \frac{m}{s}, v_i\right)$$

$$v_i := \mathbf{if}\left((\phi_r + \phi_d) \le \psi_i, v2_i, v_i\right)$$

$$v_i := \mathbf{if}\left((\phi_r + \phi_d + \phi_f) \le \psi_i, 0\ \frac{m}{s}, v_i\right)$$

For determination of the displacement of follower we define the following function -

$$s_1(\psi) := \int_{0.001}^{\psi} v_1(x)\,dx$$

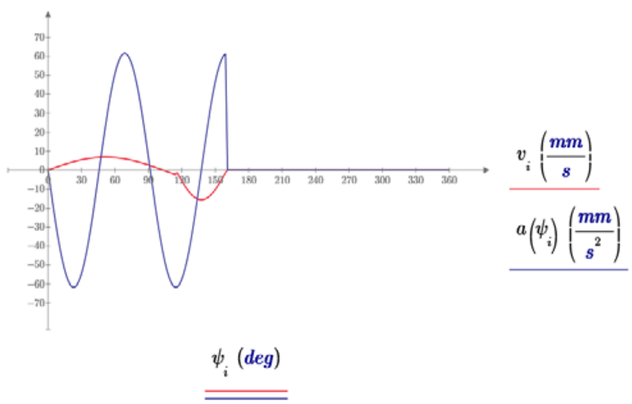
$$s_2(\psi) := \int_{\phi_r+\phi_d+\phi_f}^{\psi} v_2(x)\,\mathrm{d}x$$

And compute

$$s1_i := s_1\left(\psi_i\right) \cdot s^2$$

$$s2_i := s_2\left(\psi_i\right) \cdot s^2$$

Graph of velocity and acceleration profiles throughout one rotation is given by -



Graph. 4.1. Velocity and Acceleration versus cam angle.

The displacement profile for one cycle of cam's motion can be determined by the following logic –

$$s_i := \mathbf{if}\left(0 \le \psi_i, s1_i, 0\ \boldsymbol{m}\right)$$

$$s_i := \mathbf{if}\left(0 \le \psi_i, 0\ \boldsymbol{m}, s_i\right)$$

$$s_i := \mathbf{if}\left(\left(\phi_r+\phi_d\right) \le \psi_i, s2_i, s_i\right)$$

$$s_i := \mathbf{if}\left(\left(\phi_r+\phi_d+\phi_f\right) \le \psi_i, 0\ \boldsymbol{m}, s_i\right)$$

$$\theta_p := 45$$

The pressure angle can be determined by following function -

$$f\left(\varepsilon, s, v, R_o\right) := \operatorname{atan}\left(\frac{\varepsilon - v}{s + \sqrt{R_o^{\,2} - \varepsilon^2}}\right)$$

From the relation,

$$t\left(0, s_i, v_i, r_i\right) = \theta_p$$

Anyone can give resulting formula –

$$r_i := \frac{-v_i \cdot \boldsymbol{s}}{\tan\left(\theta_p\right)} - s_i$$

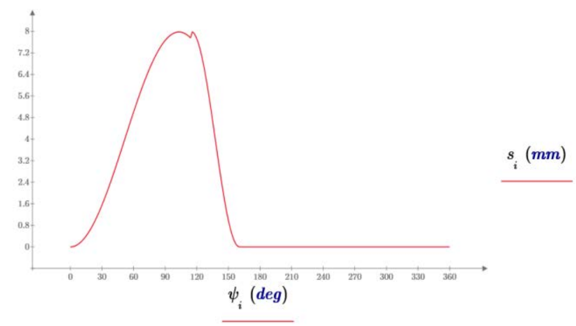
The values of pressure angle must be validated throughout a given rotation to make sure the restriction is within a limit of ±10%.

$$\theta_{0_i} := f\left(0 \cdot \boldsymbol{m}, s_i, v_i \cdot \boldsymbol{s}, R_o\right)$$

$$\theta_{1_i} := f\left(0 \cdot \boldsymbol{m}, s_i, v_i \cdot \boldsymbol{s}, 1.1 \cdot R_o\right)$$

$$\theta_{2_i} := f\left(0 \cdot \boldsymbol{m}, s_i, v_i \cdot \boldsymbol{sec}, 0.9 \cdot R_o\right)$$

Displacement variation in one rotation is given by -



Graph. 4.2. Displacement versus cam angle.

According to the theory, the function determines the polar radius of the points on the pitch curve is –

$$g\left(s, R_o, \varepsilon\right) := \sqrt{s^2 + R_o^{\,2} + 2 \cdot s \cdot \sqrt{R_o^{\,2} - \varepsilon^2}}$$

The function allows to find the angle between of the radius vector of the roller's centre (pitch curve point) and the direction of the follower motion.

$$F\left(s, R_o, \varepsilon\right) := \operatorname{asin}\left(\frac{\varepsilon}{g\left(s, R_o, \varepsilon\right)}\right)$$

The function determines the polar angle of the roller's centre (pitch curve point) is –

$$h\left(\psi, s, R_o, \varepsilon\right) := \psi - F\left(s, R_o, \varepsilon\right) + \operatorname{asin}\left(\frac{\varepsilon}{R_o}\right)$$

The function determines an angle between the radius vector of roller's centre and the common normal is –

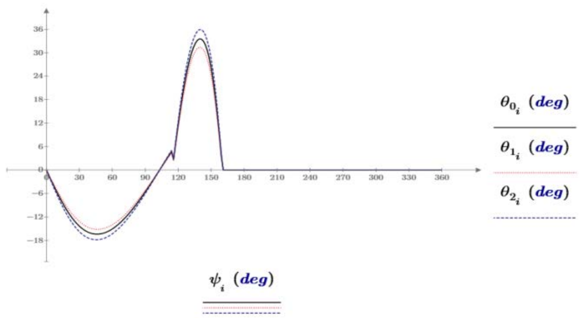
$$\delta\left(s, v, R_o, \varepsilon\right) := f\left(\varepsilon, s, v, R_o\right) - F\left(s, R_o, \varepsilon\right)$$

The polar radius of a point on the cam's profile can be determined by function –

$$G\left(s, v, R_o, r_r, \varepsilon\right) := \sqrt{\left(g\left(s, R_o, \varepsilon\right)\right)^2 + \left(r_r\right)^2 - 2 \cdot r_r \cdot g\left(s, R_o, \varepsilon\right) \cdot \cos\left(\delta\left(s, v, R_o, \varepsilon\right)\right)}$$

The function determines also the polar radius of a point on the pitch circle curve. If roller radius is zero (rr = 0).

Verifying pressure angles throughout one rotation of the cam as follows –



Graph. 4.3. Pressure angle versus angle of cam.

To find the angle between the radius vector of the roller's centre and the radius vector of the common point of the roller and cam's profile the function used is -

$$H(s,v,R_o,r_r,\varepsilon) := \operatorname{acos}\left(\frac{(g(s,R_o,\varepsilon))^2 + (G(s,v,R_o,r_r,\varepsilon))^2 - (r_r)^2}{2 \cdot g(s,R_o,\varepsilon) \cdot G(s,v,R_o,r_r,\varepsilon)}\right)$$

The function determines the polar angle of a point of cam's profile at the period of the rise of the follower is –

$$\Gamma(\psi,s,v,R_o,r_r,\varepsilon) := h(\psi,s,R_o,\varepsilon) + H(s,v,R_o,r_r,\varepsilon)$$

And the function determines the polar angle of a point of cam's profile at the period of fall of the follower is -

$$\Gamma_1(\psi,s,v,R_o,r_r,\varepsilon) := h(\psi,s,R_o,\varepsilon) - H(s,v,R_o,r_r,\varepsilon)$$

The polar angle of a point of cam's profile over one cycle of cam's rotation can be determined by formula -

$$\Phi(\psi,s,v,R_o,r_r,\varepsilon) := \text{if}\left(\psi \le \phi_r, \Gamma(\psi,s,v,R_o,r_r,\varepsilon), \Gamma_1(\psi,s,v,R_o,r_r,\varepsilon)\right)$$

Now compute for the base circle and roller radii provided as requirements -

$$r0_i := G\left(s_i, v_i \cdot sec, R_o, 0\ m, 0\ m\right)$$

$$\psi0_i := \Phi\left(\psi_i, s_i, v_i \cdot sec, R_o, 0\ m, 0\ m\right)$$

Let us now consider the variables -

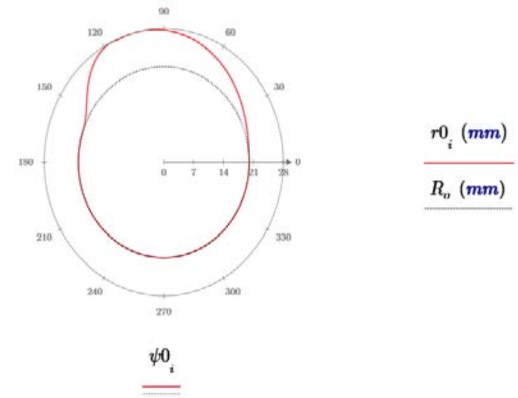
$$x1_i := R_o \cdot \cos(\psi_i)$$

$$x0_i := r0_i \cdot \cos(\psi0_i)$$

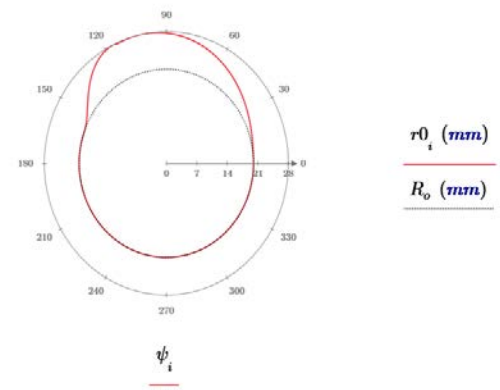
$$j := 0..(N-1)$$

$$y1_i := R_o \cdot \sin(\psi_i)$$

$$y0_i := r0_i \cdot \sin(\psi0_i)$$



Graph. 4.4. The profile of the cam, for per design study and parameters supplied.



Graph. 4.5. The cam profile in this study.

$$a_j := \frac{2 \cdot \pi}{N-1} \cdot j$$

Combining these arrays together in 3-column matrix to return PTC Creo -

$$z0 := 0 \cdot x0$$

$$curve := \text{augment}(z0, x0, y0)$$

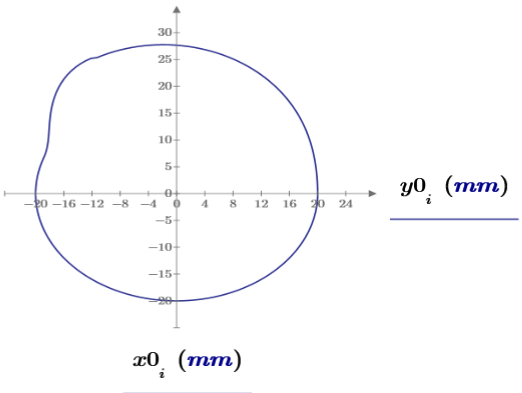
$$curve := \text{stack}(curve, \text{submatrix}(curve, 0, 0, 0, 2))$$

$$\text{rows}(curve) = 201$$

Final cam profile is given by -

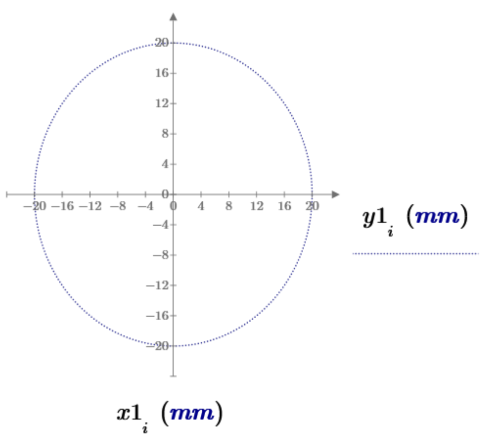
$$curve = \begin{bmatrix} 0 & 20 & 0 \\ 0 & 19.996 & 0.632 \\ 0 & 19.984 & 1.264 \\ 0 & 19.963 & 1.897 \\ 0 & 19.935 & 2.531 \\ 0 & 19.898 & 3.168 \\ & & \vdots \end{bmatrix} mm$$

This curve gives the exact cam profile as per design study and parameter supplied.



Graph. 4.6. Same cam profile above, depicted in rectangular co-ordinate system.

The Fig. 4.1. shows Mathcad procedure for design of disc cam with roller follower.



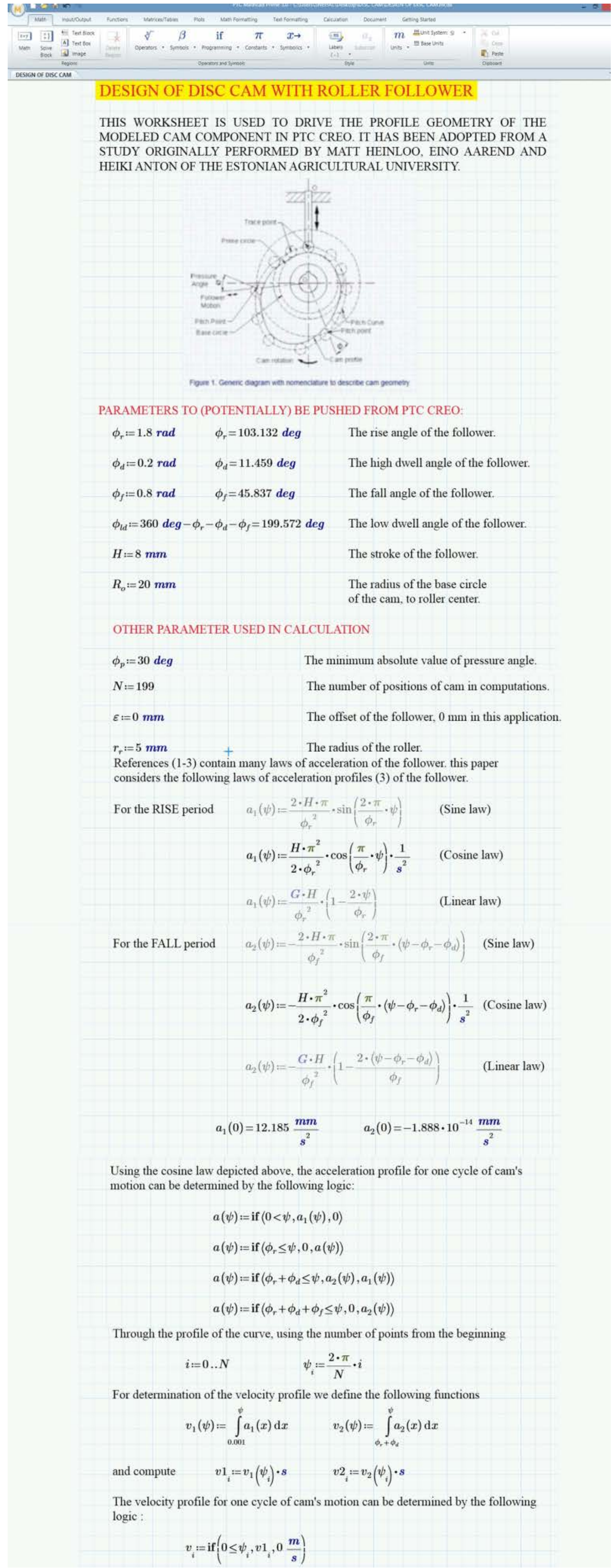
Graph. 4.7. Cam profile in rectangular system.

V. CREO PARAMETRIC TO MATHCAD PRIME INTEGRATION

Mathcad Prime procedure integrated with Creo Parametric. There is provided facility in Creo Parametric in Analysis tab for integration. This section explains integration of Creo Parametric with Mathcad Prime. Brief process steps gives idea for integration of Creo Parametric to Mathcad Prime.

INTEGRATION PROCESS STEPS:

Create a new file with name DISC_CAM as a part and solid. Use default template. Select dimension type and default environment for modelling is launches.



DESIGN OF DISC CAM

DESIGN OF DISC CAM WITH ROLLER FOLLOWER

THIS WORKSHEET IS USED TO DRIVE THE PROFILE GEOMETRY OF THE MODELED CAM COMPONENT IN PTC CREO. IT HAS BEEN ADOPTED FROM A STUDY ORIGINALLY PERFORMED BY MATT HEINLOO, EINO AAREND AND HEIKI ANTON OF THE ESTONIAN AGRICULTURAL UNIVERSITY.

Figure 1. Generic diagram with nomenclature to describe cam geometry

PARAMETERS TO (POTENTIALLY) BE PUSHED FROM PTC CREO:

$\phi_r := 1.8\ rad$ $\phi_r = 103.132\ deg$ The rise angle of the follower.

$\phi_d := 0.2\ rad$ $\phi_d = 11.459\ deg$ The high dwell angle of the follower.

$\phi_f := 0.8\ rad$ $\phi_f = 45.837\ deg$ The fall angle of the follower.

$\phi_{ld} := 360\ deg - \phi_r - \phi_d - \phi_f = 199.572\ deg$ The low dwell angle of the follower.

$H := 8\ mm$ The stroke of the follower.

$R_o := 20\ mm$ The radius of the base circle of the cam, to roller center.

OTHER PARAMETER USED IN CALCULATION

$\phi_p := 30\ deg$ The minimum absolute value of pressure angle.

$N := 199$ The number of positions of cam in computations.

$\varepsilon := 0\ mm$ The offset of the follower, 0 mm in this application.

$r_r := 5\ mm$ The radius of the roller.

References (1-3) contain many laws of acceleration of the follower. this paper considers the following laws of acceleration profiles (3) of the follower.

For the RISE period $a_1(\psi) := \frac{2 \cdot H \cdot \pi}{\phi_r^2} \cdot \sin\left(\frac{2 \cdot \pi}{\phi_r} \cdot \psi\right)$ (Sine law)

$a_1(\psi) := \frac{H \cdot \pi^2}{2 \cdot \phi_r^2} \cdot \cos\left(\frac{\pi}{\phi_r} \cdot \psi\right) \cdot \frac{1}{s^2}$ (Cosine law)

$a_1(\psi) := \frac{G \cdot H}{\phi_r^2} \cdot \left(1 - \frac{2 \cdot \psi}{\phi_r}\right)$ (Linear law)

For the FALL period $a_2(\psi) := -\frac{2 \cdot H \cdot \pi}{\phi_f^2} \cdot \sin\left(\frac{2 \cdot \pi}{\phi_f} \cdot (\psi - \phi_r - \phi_d)\right)$ (Sine law)

$a_2(\psi) := -\frac{H \cdot \pi^2}{2 \cdot \phi_f^2} \cdot \cos\left(\frac{\pi}{\phi_f} \cdot (\psi - \phi_r - \phi_d)\right) \cdot \frac{1}{s^2}$ (Cosine law)

$a_2(\psi) := -\frac{G \cdot H}{\phi_f^2} \cdot \left(1 - \frac{2 \cdot (\psi - \phi_r - \phi_d)}{\phi_f}\right)$ (Linear law)

$a_1(0) = 12.185\ \frac{mm}{s^2}$ $a_2(0) = -1.888 \cdot 10^{-14}\ \frac{mm}{s^2}$

Using the cosine law depicted above, the acceleration profile for one cycle of cam's motion can be determined by the following logic:

$a(\psi) := \text{if}\left(0 < \psi, a_1(\psi), 0\right)$

$a(\psi) := \text{if}\left(\phi_r \le \psi, 0, a(\psi)\right)$

$a(\psi) := \text{if}\left(\phi_r + \phi_d \le \psi, a_2(\psi), a_1(\psi)\right)$

$a(\psi) := \text{if}\left(\phi_r + \phi_d + \phi_f \le \psi, 0, a_2(\psi)\right)$

Through the profile of the curve, using the number of points from the beginning

$i := 0..N$ $\psi_i := \frac{2 \cdot \pi}{N} \cdot i$

For determination of the velocity profile we define the following functions

$v_1(\psi) := \int_{0.001}^{\psi} a_1(x)\, dx$ $v_2(\psi) := \int_{\phi_r + \phi_d}^{\psi} a_2(x)\, dx$

and compute $v1_i := v_1(\psi_i) \cdot s$ $v2_i := v_2(\psi_i) \cdot s$

The velocity profile for one cycle of cam's motion can be determined by the following logic :

$v_i := \text{if}\left(0 \le \psi_i, v1_i, 0\ \frac{m}{s}\right)$

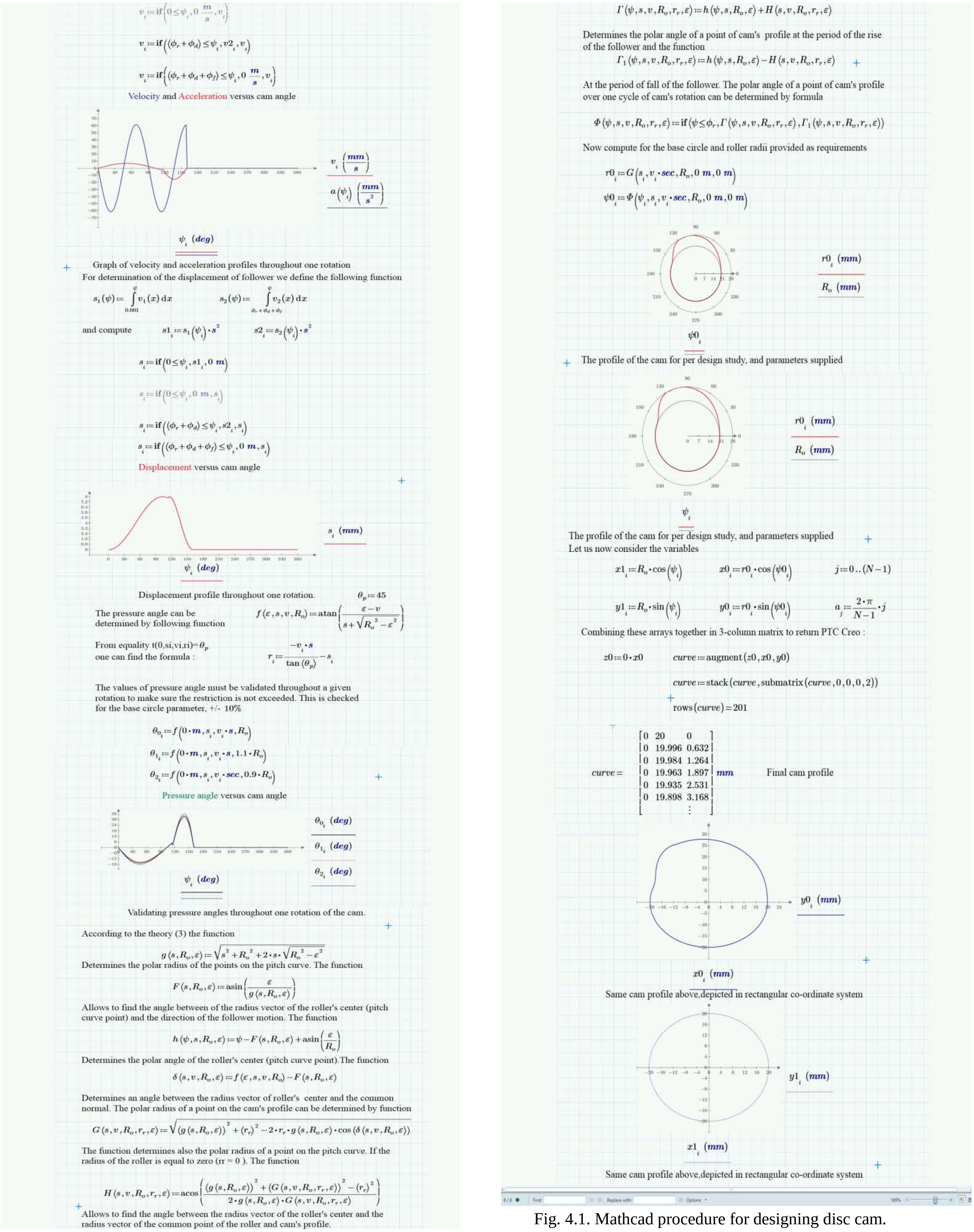


Fig. 4.1. Mathcad procedure for designing disc cam.

In analysis tab, go to prime analysis and then load Mathcad worksheet for modelling disc cam.

After loading Mathcad file, assign input and output for disc cam. Then save the Mathcad worksheet.

Create prime to Creo parameter mapping. Right click and Select prime output parameter. Parameter selection pop up and select scale parameter as profile.

Now prime analysis tab shows mapped value and then compute. In add feature tab, add name for analysis and close it.

Profile analysis profile points for disc cam in Fig. 4.2.

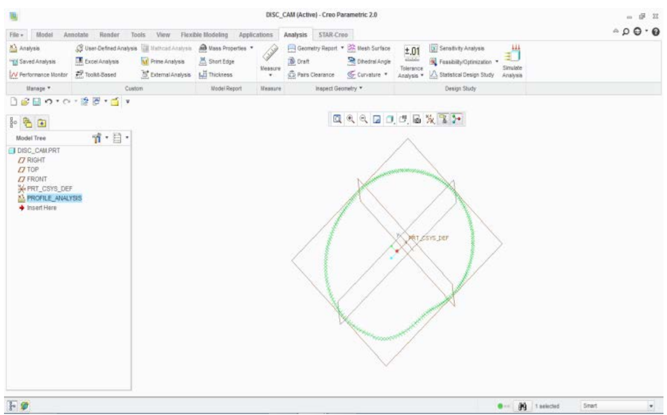


Fig. 4.2. Profile points for disc cam generation.

Right click on PROFILE_ANALYSIS and click on edit definition. Analysis tab shows result datums for profile. Now click profile_40 and define datum nature for profile. In definition tab, the datum nature of profile by default is Yes. Modify it to No. In definition tab, the datum nature of curve profile by default is No. Modify it to Yes. Save changes made successfully by regeneration.

Sketch of profile for disc cam generated successfully by regeneration.

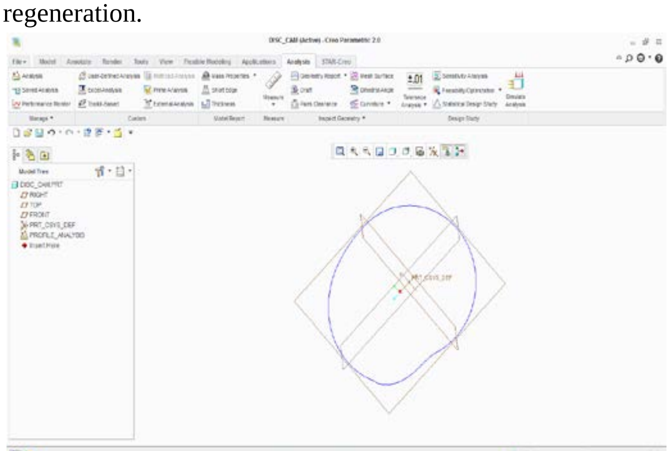


Fig. 4.3. Disc cam profile sketch.

Select sketch plane, click sketch and assign offset for loop of selected profile curve as 0 and save changes. Then apply changes and close sketch tab. Extrude to 20 mm.

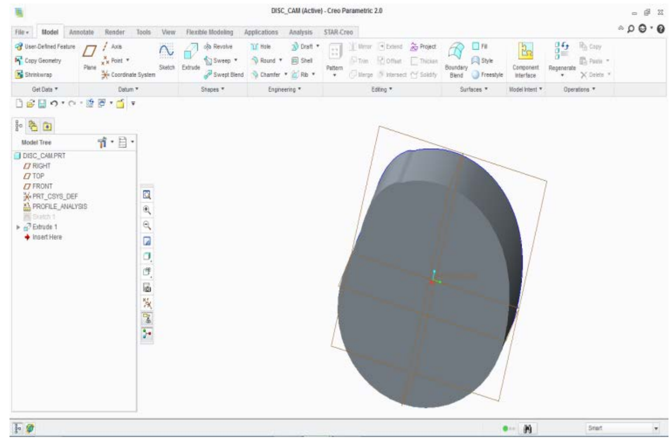


Fig. 4.4. Extruded sketch of disc cam.

Now a disc cam defined by radius of roller, radius of base circle of cam, offset and rise angle with specified dimensions in Creo Parametric 2.0 is ready.

Go to sketch of disc cam. Right click on sketch and select feature. In feature info, note down Feature's Dimension ID for the dimension that you want to integrate with Mathcad worksheet.

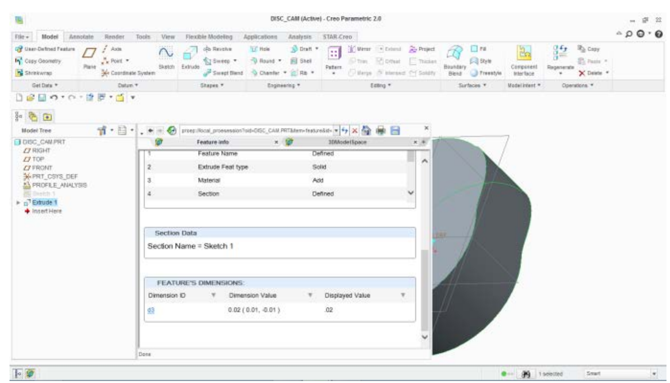


Fig. 4.5. Notation of Feature's Dimension ID.

Note down notation to feature in Creo Parametric. Specify scale parameter and scale. Go to tools tab and click parameters tab. Add parameter as scale to 1. In analysis, prime analysis and load Mathcad worksheet for integration.

After loading Mathcad file, assign scale to 1 in input and the dimension as output as extrude length which is modified using integration. Then save the Mathcad worksheet.

Now go to Creo prime analysis interface. Click Auto-map and create Creo parameter to prime mapping. Select Creo scale parameter.

After this, right click and select prime input scale. Click ok. Now proceed to Prime to Creo parametric mapping.

Create prime to Creo parameter mapping. Right click and select output of Mathcad prime. Select T parameter.

Now prime analysis tab shows mapped value and then click compute. Add feature tab is now active, add name for analysis and close it.

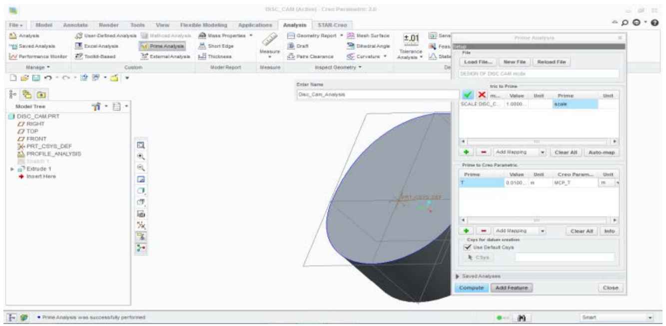


Fig. 4.6. Mapping results and computation.

Go to tools tab and click d = relations tab. Relations pop up opens and select feature in place of part. Specify relations in feature parameter. Click on local parameter. Add parameter to relations and equate it with previously note down Feature's Dimension ID. Verify relations. Click ok.

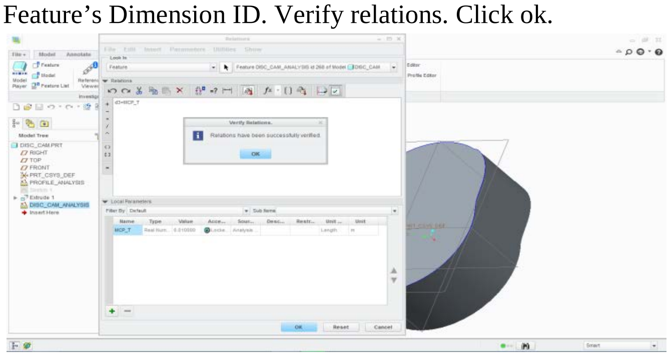


Fig. 4.7. Specifying relations and its verification.

The software gives yellow indication. Click on indication, it show regeneration tab with sketch which is unregenerated. Click on regenerate and software to regenerate drawing. Then right click on sketch and edit definition for checking dimensions.

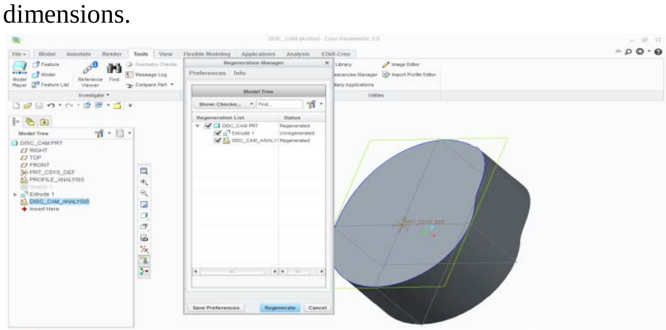


Fig. 4.8. Regeneration of sketch from extrusion 0.02 inch to 0.01 inch.

Then complete regeneration and check extrusion dimension modified to 0.254 mm. It shows new measure of 0.254 mm which is in Mathcad worksheet. Here, extrusion dimension is modified using integration process.

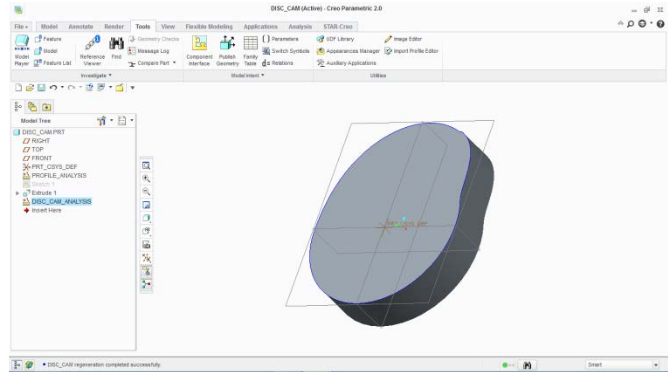


Fig. 4.9. Regenerated disc cam

This concludes the integration process. If you want to modify extrusion again then follow the steps discussed below.

VI. CONCLUSION

Camshaft lobe profile generation is very tedious and time consuming process in CAD. This process can be simplified to great extent by using methodology described in this paper. The main result of this study is the mathematical formulation of design procedure for disc cam at various operating points across the realistic operating range. This design procedure can be used for other engines disc cams with desired modification for designing camshaft.

Analytical calculations are highly complex and very difficult to perform using MS Excel. So Mathcad is a good solution for performing this type of complex calculations and formulations.

After performing whole calculations, the template is used to integrate with actual CAD model of the components. In this paper, Integration process for disc cam is shown in detail using Creo and Mathcad. The CAD model will be automatically modified as dimension in Mathcad worksheet modifies after successful regeneration in Creo parametric.

The creation of procedures in Mathcad results in quick generation of output instead of manually changing every single dimension of model.

VII. FUTURE SCOPES

Most of design procedures created in Mathcad, such that it will reduce work of design engineer and helpful for development of CAD model. Profile generated in CAD can be linked to CNC programming to automatically create the profile.

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