A Case Study of Modelling Concave Globoidal Cam

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1. Introduction

Globoidal cam mechanisms are widely used in industry. Compared to other cam-follower systems, the globoidal cam-follower mechanisms have many advantages, such as: compact structure, high loading capacity, low noise, low vibration, and high reliability. They are widely used in machine tools, automatic assembly lines, paper processing machines, packing machines, and many automated manufacturing devices.

In term of the shape, globoidal cam is one of the most complicated cams. The most important task when modelling the globoidal cams is to represent their working surfaces. The working surfaces of the globoidal cams are the surfaces that contact with the roller surfaces. These surfaces are very complex and it is very difficult to create them accurately.

Up to now, a number of works dealing with finding the way to describe accurately these surfaces have been proposed.

Some researchers derived mathematically expressions for the surface geometry of the globoidal cam with cylindrical, hyperboloid, or spherical rollers, based on coordinate transformation, differential geometry, and theory of conjugate surfaces (Yan & Chen, 1994 & 1995; Yan-ming, 2000; Cheng, 2002; Lee & Lee, 2001 & 2007; Chen & Hong, 2008). They developed their own programs, which were written in Visual Basic, C or C++ languages, to assist themselves in studying. Some programs can draw and display the draft of the cam contour, or create the solid model. Some can create the data of the cam curve profile which will be the input data for CAD/CAM software such as Unigraphics to build the CAD model (Chen & Hong, 2008). Some other researchers also described mathematicaly the cam surface, but they used computer to develop a package, which was a combination of AutoCAD R14, 3D Studio Max, and VBA, to generate the surfaces of the roller gear cam (En-hui et al., 2001). In addition, some researchers studied to create the globoidal cam with conical rollers from machining point of view (Tsay & Lin, 2006). They represented the surface geometry of the cam as the swept surfaces of the tool paths. In their study, the expression of a surface normal, a rule surface and its offset, meshing vectors and meshing angles were introduced to define the accurate swept surfaces generated by the roller follower, and a program in C++ language developed to generate the surface coordinates of the cam.

In general, the works mentioned above have used the mathematical expressions for the globoidal cam surfaces and various cam laws as the input data to generate the cam surfaces.

From machining point of view, the globoidal cam surfaces can be determined by corresponding angular displacements of both the cam and the driven member (Koloc & Vaclavik, 1993). These angular displacements can be extracted from the NC program generated by some special sofwares that are specialized for cam mechanisms. They can also be obtained from the follower displacement equations. In this study, the concave globoidal cam with swinging roller follower is modeled from angular input and output displacements.

The objective of the chapter is to introduce some effective methods for modelling concave globoidal cam. These methods can be implemented by using commercial CAD/CAM sofwares. In the chapter, Pro/ENGINEER® Wildfire 2.0 is used to create the cams for the illustrative example that we have recently done for industry in Czech Republic. In this case study, the input data for modelling are the angular input and output displacements of the cam and the follower. Furthermore, besides modelling methods, some important techniques that are useful for designers to find out the most accurate model are also represented. In this chapter, the terms “globoidal cam surface(s)” and “cam surface(s)” refer the working surface(s) of the globoidal cam.

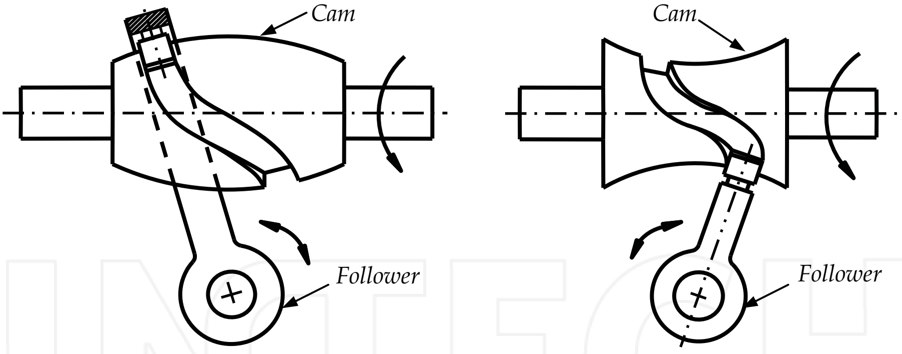
The outline of the chapter is as follows. Section 2 presents the theoretical background of concave globoidal cam. In section 3 we describe in detail some modelling methods that can be used to create the globoidal cam surfaces. An application example is presented in Section 4. Finally, conclusion remarks are given in Section 5.

2. Theoretical background of concave globoidal cam

There are two types of globoidal cams. The first one is the globoidal cam that has a groove on its surface and the roller follower oscillates when the cam rotates. This type has two subtypes which are convex and concave (Figure 1). These cams are used for small angles of follower oscillation. The second one has one or more ribs on a globoidal body. This type is also called roller gear cam or Ferguson drive (Rothbart, 2004). The two surfaces of the rib always contact with the rollers (cylindrical, spherical or conical) of the follower. This follower may oscillate about its axis or have an intermittent rotation. Figure 2 shows two subtypes of the concave globoidal cam: the concave globoidal cam with an oscillating follower and the concave globoidal cam with an indexing turret follower. The rib of these cams looks like a thread or a blade so that sometimes they can be called thread-type or blade-type globoidal cams. In this study, the single thread-type is the globoidal cam that we will deal with.

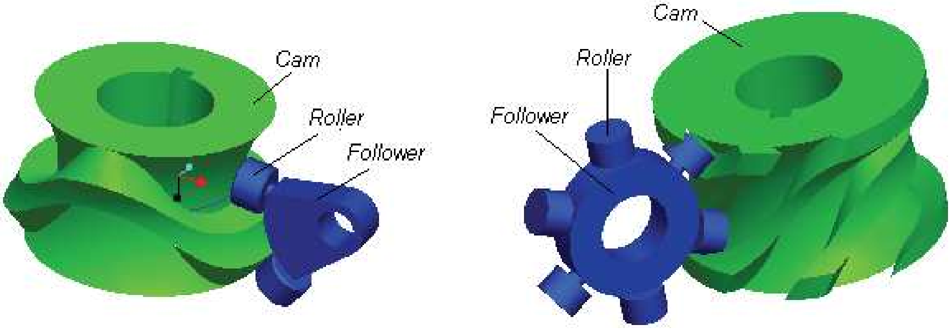
Figure 3 illustrates the geometrical relationships between a concave globoidal cam with an oscillating follower. According to the structure of the globoidal cam, as can be seen from Figure 2&3, the symmetrical plane of the follower contains the cam axis and the axes of the rollers intersect at a point that lies on the follower axis. In Figure 3, the development plane is the plane that is normal to the axis of the roller and located anywhere along the length of the roller. The intersection point between the development plane and the axis of the roller is the pitch point (P). Datum plane is the plane normal to the cam axis and contains the follower axis. The angular displacement of the roller is measured from this plane.

The following are some parameters related to a globoidal cam-follower system (Koloc & Vaclavik, 1993; Reeve, 1995).



(a) Convex cam (b) Concave cam

Fig. 1. Globoidal cam-groove type, oscillating follower



(a) Oscillating follower (b) Indexing turret follower.

Fig. 2. Globoidal cam - thread type.

α - angular input displacement (the rotation angle of the cam).

β - angular output displacement from datum plane (the rotation angle of the follower). β has a relationship with α and it can be expressed by function $\beta = f(\alpha)$, (En-hui et al., 2001).

β^0 – angle from datum plane to start of follower motion, measured in direction of motion. If the start point is encountered after the datum plane then β^0 is positive.

β^1 – angle between the axis of the upper roller with the datum plane. At the beginning, when the upper roller is at the starting point then $\beta^0 = \beta^1$.

β^2 – angle between the axis of the lower roller with the datum plane.

t - distance between the axis of the follower to the end of the roller, measured along the roller axis.

e – clearance between the end of the roller and the cam body.

F - distance from the axis of the follower to the pitch point.

C - distance between the cam axis and the turret axis.

R - perpendicular distance from cam axis to the pitch point, expressed as

$$R = C - F.\cos(\beta^1) \tag{1}$$

h – distance from the pitch point to the datum plane. It is the height of the point P and presented as

$$h = F.\sin(\beta^1) \tag{2}$$

Obviously, the coordinates of the pitch points on the rollers can be calculated if the angular input and output displacements are known. From these coordinates and some other information, the pitch surfaces of the cam can be modeled.

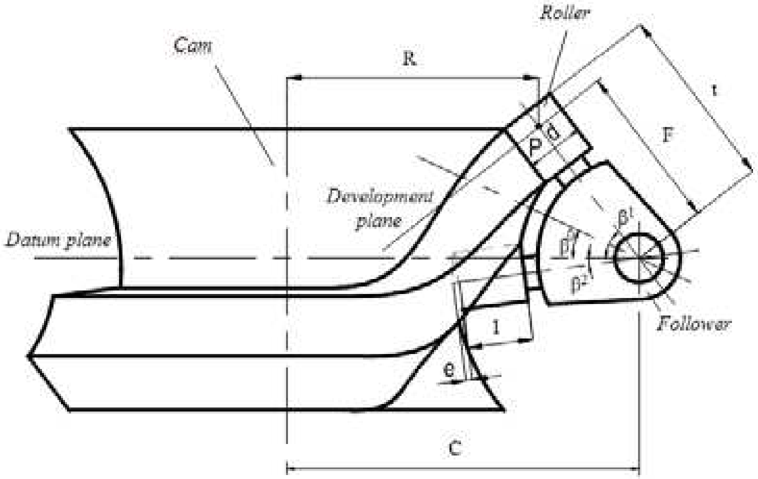


Fig. 3. Globoidal cam- oscillating follower arrangement

3. Modelling methods

There are some methods used to model concave globoidal cams. The most important task in the modelling procedure is to create the working surfaces of the cam. Once these surfaces are created, other surfaces of the cam can be easily formed later. Here, we introduce two groups of methods that can be used to create the cam surfaces, namely *Pitch surface-based methods* and *Standard cutter-based method*.

3.1 Pitch surface-based methods

In a globoidal cam-follower system, when the follower rotates, the locus of the roller axis will generate a ruled surface (pitch curved surface) in space (Tsay & Lin, 2006). The two axes of two rollers in this case study will generate two pitch curved surfaces. The working surfaces of the cam can be obtained from the pitch surfaces by offsetting them a distance that is equal to the radius of the roller.

There are several methods to get the pitch surface. The followings are three methods that can be used to create the pitch surface.

3.1.1 Graphs-based method (method 1)

Sweep a straight line with two constraints (Figure 4): (i) the angle between this line and the datum plane varies when the cam rotates and its value is β^i_j; (ii) the coordinates of the pitch point P on this line, in the cylindrical coordinate system, corresponding with the input angular displacement α_j, satisfy the formulas below.

$$h^i_j = F.\sin\beta^i_j \tag{3}$$

$$R^i_j = C - F.\cos\beta^i_j \tag{4}$$

where i = 1, 2, corresponding with the upper and the lower pitch surfaces; j = 1,2,…,n, corresponding with the angular output displacements.

The relationship between pairs α and β, h and β, R and β can be expressed in graphs. These graphs are useful for modelling the cam in commercial CAD/CAM softwares.

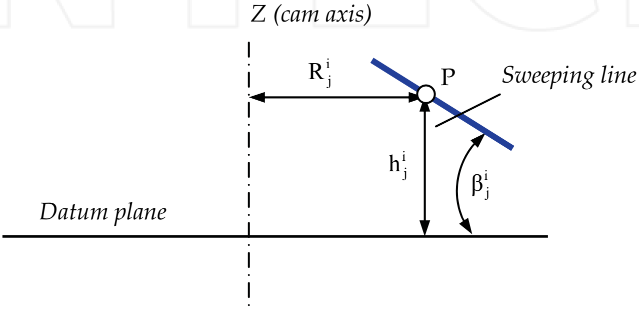


Fig. 4. Principle of graphs-based method

3.1.2 Open section-based method (method 2)

This method is similar to the previous method but here the two pitch surfaces are created at the same time. These surfaces are made by sweeping an "open section" which consists of three straight lines. Two of them are collinear with the axes of the two rollers. The last one connects them together.

3.1.3 Curves- based method (method 3)

Sweep a straight line that is collinear with the roller axis. The two end points of this line must lie on two curves (Figure 6). One of these curves is a circle in the datum plane. This circle goes through the intersection point of the roller axes and its center is in the cam axis and it is also called the origin trajectory. The other curve is a three-dimensional (3D) curve. This 3D curve is the locus of a point, which located on the roller axis (it can be the pitch point), when the follower rotating. The coordinates of that point satisfy formulas (3) and (4) above.

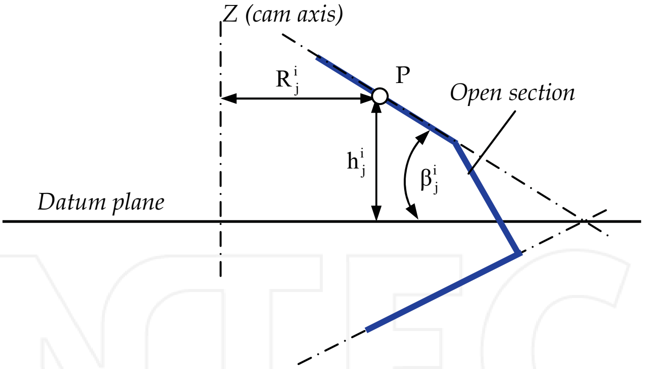


Fig. 5. “Open section” method

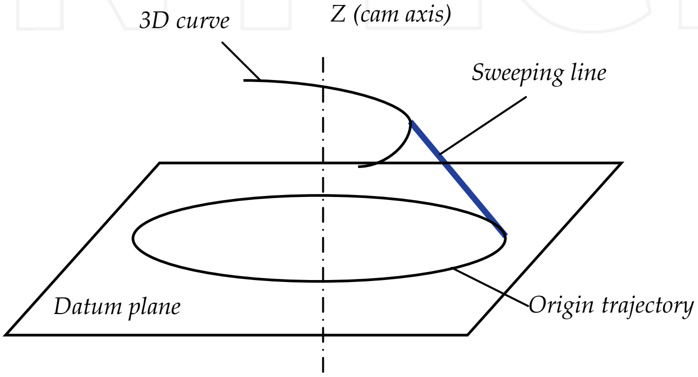


Fig. 6. Principle of curves- based method

3.1.4 Standard cutter-based method (method 4)

An end mill cutter can generate the surfaces of a globoidal cam. If the diameters of the cutter and the roller are equal, the motion of the cutter will be similar to that of the roller in the machining process, and of course, the cutter must rotate about its axis (roller axis). The sweep surface of the tool path can represent the working surface of the cam. The following is one way that can be used to get the cam surface.

Cut a bank by sweeping a rectangular section (Figure 7) to form the cam surfaces if the following constrains are performed:

(1) The width of the section is equal to the diameter of the roller. The length of the section satisfies the following formula.

$$L = t + e \tag{5}$$

where, L is the length of the rectangular section, t and e are two geometrical parameters of the cam which mentioned in section 2.

(2) Two points on the section, which are intersection points between the symmetry axis of the section and its edges, must follow two 3D curves. These curves are loci of two points, which are on the roller axis, when the follower rotates. One of these curves is the origin trajectory. The curves which are used in the curves-based method can be applied here.

(3) This section plane always contains the cam axis.

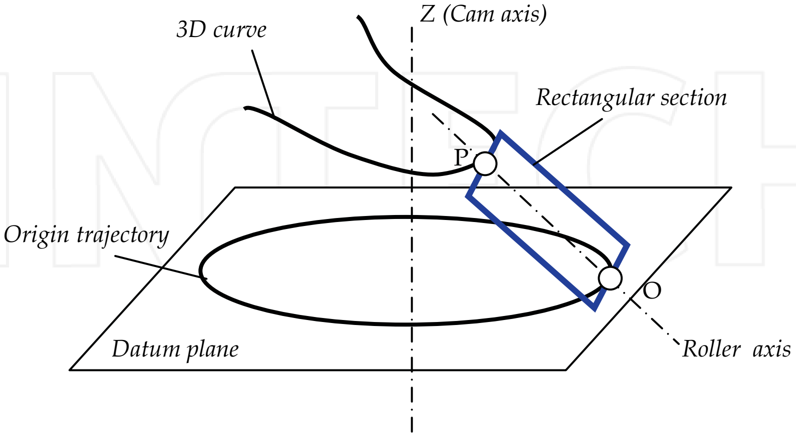


Fig. 7. Standard cutter-based method

The globoidal cam can be modeled by using CAD/CAM softwares such as CATIA, Unigraphics NX, Pro/Engineer.... The four methods above can be implemented in Pro/Engineer. In theory, geometric errors may exist on every model. These errors may be so very high that the model cannot be acceptable. Hence, after modelling, models must be checked to find out the best one among them. In this study, Pro/Engineer Wildfire 2.0 is used to create the globoidal cam. The implementation of those methods is presented in a form of an illustrated example in the next section. Besides, some other important tasks to check the model are included as well.

4. Application example

4.1. Input data and calculations

Given a concave globoidal cam with an oscillating follower that has two cylindrical rollers. The angle between two axes of the rollers is 60^0. The increment of the input angle of the cam is 0.2^0, starts from 0 and ends at 360^0. The angular input and output displacements are given in a table that consists of 1800 pairs of corresponding angles. Some of them are presented in Table I in the appendix. To observe easily, the relationship between the angular input and output displacements is showed in Figure 8. The following are some other parameters of the system, which are showed in Figure 2: d = 25.5 mm, l = 16 mm, C= 107.8 mm, t = 58.7 mm, $\beta_0 = 7.49^0$, e = 2.3 mm.

There are some calculations that must be done before making the models as follows:

(1) Calculating the angular outputs included β_0.

(2) Calculating the angle β_j^1 and β_j^2.

$$\beta_j^1 = \beta_j + \beta^0 \tag{5}$$

$$\beta_j^2 = 60 - \beta_j^1 \tag{6}$$

(3) Calculating the coordinates of two pitch points for each pitch surface. The pitch points are located at the distance F= 59.7 mm on the roller axes.

All the calculations are done in Microsoft Excel 2003.

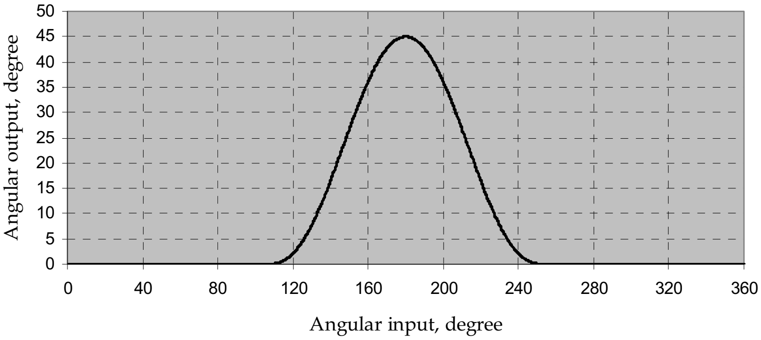


Fig. 8. Angular input/output displacements

4.2. Modelling procedures and results

The following are the main steps to create the globoidal cam by using four methods described above in Pro/Engineer Wildfire 2.0. The accuracy of the system is set to 0.0005 to get high accurate models.

The graphs-based method

(1) Create a revolution surface of the globoidal body of the cam (Figure 9a).

(2) Create 3 graphs for the angle between the sweeping line and the datum plane (Figure 9b), the height of the pitch point on the sweeping line, and the distance (radius) from the pitch point to the cam axis. These graphs show the dependence of the three above parameters on the angular output displacement of the cam.

(3) Create the upper pitch surface by using the Variable Section Sweep command (Figure 9c). The origin trajectory in this case is the circle which is the intersection between datum plane and the cam body. Constrains for this command are formulas that have the form as

*sd# = evalgraph("graph_name",trajpar*360)* (7)

where

- **sd#** is the dimension which will vary. It can be **R** or **h** or **β** (Figure 3a).
- **graph_name** is the name of the graph which created in step 2, corresponding with the dimension **sd#**.

Refer (Tuong & Pokorny, 2008b) to get some more useful infomation about these graphs.

(4) Repeat steps 2 and 3 for the lower pitch surface (Figure 9c), using other three graphs.

(5) Offset the two pitch surfaces to get the working surfaces of the cam (Figure 9d).
(6) Merge all surfaces to become one and convert the united surface to solid (Figure 9e).
(7) Perform some extra cuts to get the desired cam, model 1 (Figure 9f).

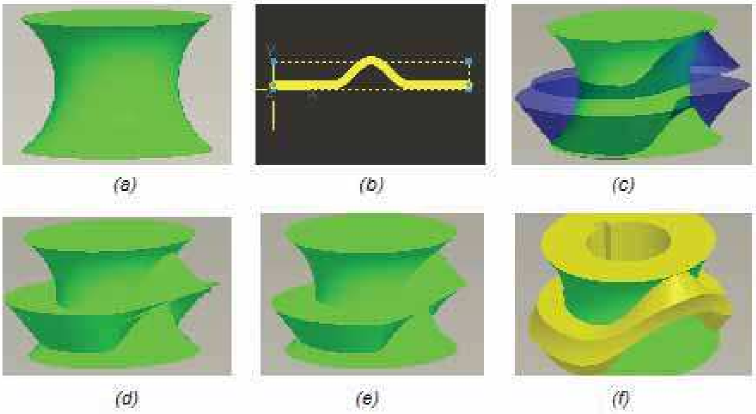


Fig. 9. Main steps of the graphs-based method

The open section-based method

(1) Create a revolution surface and 3 graphs like the first two steps in the first method.
(2) Create the two pitch surfaces at the same time by using the Variable Section Sweep command (Figure 10a) with the same constrains in step 3 in the first method.
(3) Perform steps 5, 6 & 7 as in the first method to get the solid model (Figure 10b) and the desired cam, model 2 (Figure 10c).

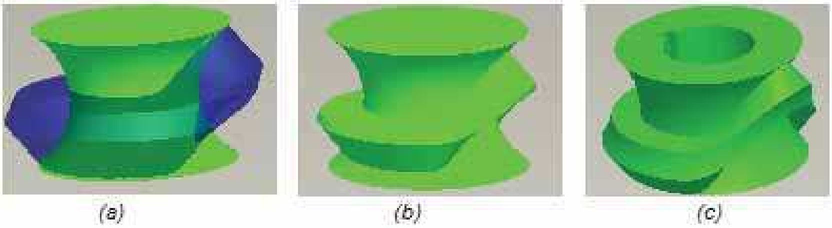


Fig. 10. Some main steps of the open section-based method

The curves-based method

(1) Create a revolution surface of the globoidal body of the cam (Figure 11a).
(2) Create the origin trajectory and two 3D curves (Figure 11b).
(3) Create the two pitch surfaces by using the Variable Section Sweep command (Figure 11c).
(4) Perform steps 5, 6 & 7 as in the first method to get the offset surfaces (Figure 11d), the solid model (Figure 11e) and the desired cam, model 3 (Figure 11f).

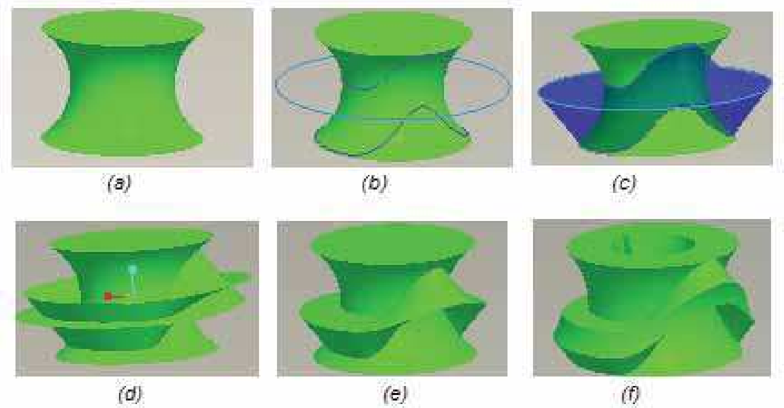


Fig. 11. Main steps of the curves-based method

The standard cutter-based method

(1) Create a revolution blank of the cam body (Figure 12a).
(2) Create the origin trajectory and two 3D curves (Figure 12b).
(3) Perform two cuts with rectangular section by using the Variable Section Sweep command (Figure 12c).
(4) Perform some extra cuts to get the desired cam, model 4 (Figure 12d).

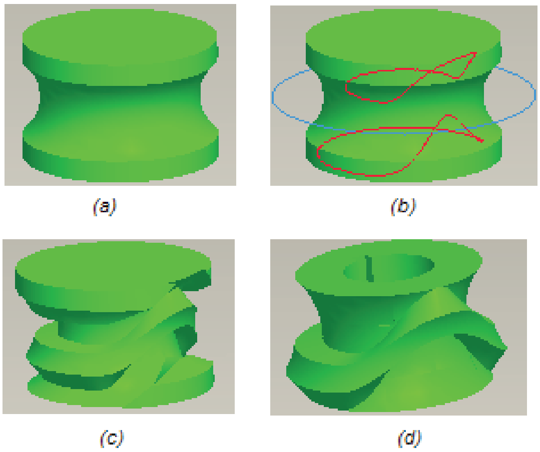


Fig. 12. Main steps of the standard cutter-based method

Among the four methods, the two first methods need more steps than the others but the modelling time is much shorter than that of the two last methods. This is because when creating the pitch surfaces in the methods which need 3D curves, the system has to interpolate the swept surface through 1800 physical points on this curve.
To see the cam easily, the pitch surfaces on four final models in figures 9 to 12 are hidden. In general, these models look great and similar. In order to choose the best one among them,

the interference between the cam and its rollers must be checked. If there is no interference and the clearance between the components is small enough, then the result is acceptable.

4.3 Making animation and checking interference

In order to make animation and verify the interference between components in the globoidal cam mechanism, first, an assembly of the cam and the follower is made. After that, use the Mechanism Design module to define the geometrical relationships of the system, make it move and analyze its motion also. Last, use a kinematics analysis to obtain information on interference between components. The following is the procedure to make animation and check interference.

(a) Creating the assembly model.
(b) Modifying Joint Axis Settings.
(c) Creating a slot-follower.
(d) Checking the assembly model.
(e) Creating servo motor.
(f) Creating and Running Analyses.
(g) Viewing results and taking measurements.

When the globoidal cam rotates, the follower will stay or rotate depending on the location of the rollers on the cam surfaces. The follower will not move when the rollers still contact with the cam surfaces in the dwell periods. To get a motion for the follower, a point on one roller axis has to trace along a 3D curve on the pitch surface. The pitch point now can be used for this purpose (point PNT0 in Figure 13). This 3D curve is available on the model 3 and model 4. This curve can be drawn on model 1 and model 2 for the purpose of checking interference. The servo motor is always applied on the cam axis so that the cam can move about its axis. Servo motor can also be applied for the follower. In this case, the slot-follower connection is omitted. Figure 13 shows the cam-follower system in the Mechanism application with the slot-follower connection.

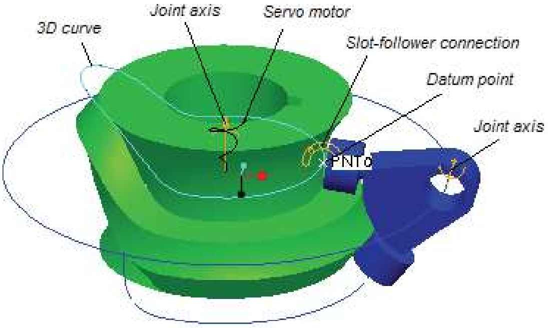


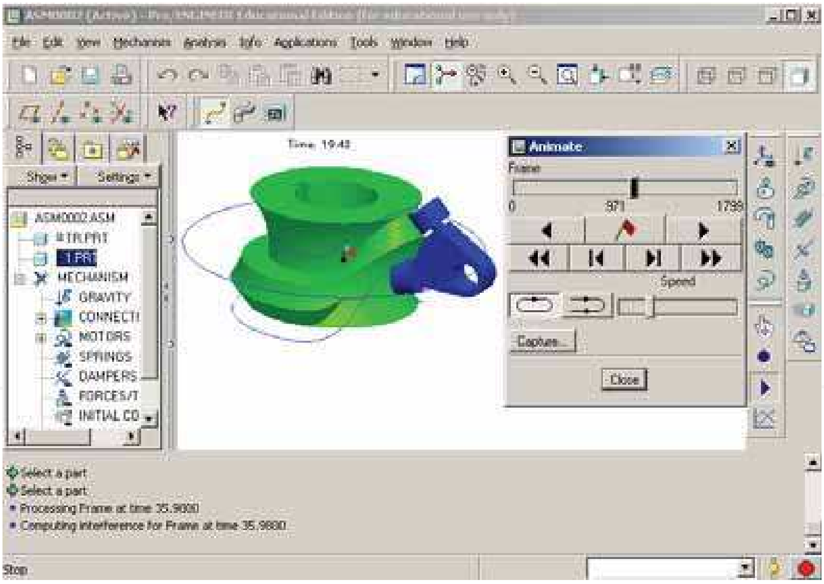
Fig. 13. Cam-follower system in Mechanism application.

During the animation, the motions of the cam and the follower are simulated, and if there is any interference between the two components, Pro/Engineer will highlight the interfered positions. Figure 14 presents the result of the animation of model 1.

In the assembly of model 1 and model 3 and their followers, there is no interference between the cam and its rollers when the cam rotates one revolution, while interferences occur in the assembly of model 2 and model 4. There are 10 positions of interference in the assembly of former, while there are a lot of positions of interferences for the latter. These interferences appear on both sides of the rib on the rise and return periods, where the curvature of working surfaces changes strongly, and can be seen in the graphic window (Figure 15). There are totally 1800 positions checked for a full revolution of the cam. The angle between two positions (called frames in Mechanism Design module) is 0.2^0. This value is similar to the increment of the input angle of the cam. In comparison with model 2 and model 4, the latter has bigger interference volumes. The result is that model 1 and model 3 can be accepted.

Although the interference does not occur between the cam surfaces of the acceptable models with their rollers, but there may have clearances between them. Thus, these clearances must be checked to ensure that they are small enough. If they are large, the errors of output angular displacements will be large and the model in this case may have to be eliminated. These clearances can be manually measured in assembly standard mode or in mechanism mode. The measuring result is that in one revolution of the cam the biggest clearances are on the rise and return periods and they are less than 0.2 micrometer for both models (Tuong & Pokorny, 2008). Obviously, these gaps also cause errors in the output angular displacements but these errors are very small and can be accepted.

In this study, the four models above were created on a notebook with 1.86 GHz Core 2 Duo processor, 2GB RAM. It took only few minutes to create the pitch surface, the most time-consuming task, for the model of the first method (graphs-based method). Meanwhile, it took quite long with the methods that used 3D curves (method 3 and 4). The similar problem happened when performing the analysis running for checking interference. Therefore, the first method is the best choice when considering the modelling methods.



```
Select a part
Select a part
• Processing Frame at time 35.9800
• Computing interference for Frame at time 35.9800
```

Fig. 14. Animation playback of model 1.

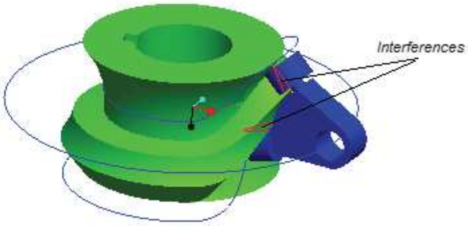
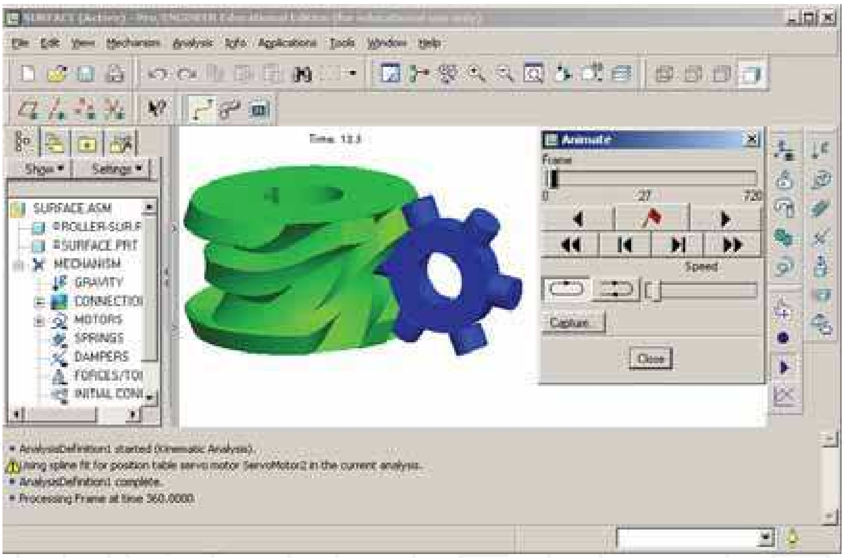


Fig. 15. Interferences (in red colour) occur between components (model 4).

In our research, besides the example above, another example for modelling concave globoidal cam with indexing turret follower has also been done (Tuong & Pokorny, 2009). In that case study, the pitch surface-based modelling method was successfully used to create the cam. Some techniques which introduced above can be used for that case. However, the modelling procedure is much more complicated than the case of the concave globoidal cam with swinging roller follower. Figure 16 shows the animation playback of the concave globoidal cam with indexing turret follower.



```
• AnalysisDefinition1 started (Kinematic Analysis).
⚠ Using spline fit for position table servo motor ServoMotor2 in the current analysis.
• AnalysisDefinition1 complete.
• Processing Frame at time 360.0000
```

Fig. 16. Animation playback of the concave globoidal cam with indexing turret follower.

5. Conclusion

In this study, four modelling methods are developed to create the concave globoidal cam. These methods are implemented in Pro/Engineer® Wildfire 2.0 using the same input data of a concave globoidal cam with an oscillating follower. After verifying the four models corresponding with the four methods, it can be said that the model which is created from the graphs-based method is the best one because it meets the required accuracy and the modelling time is short. This method is easy to conduct in Pro/Engineer, which is one of the most powerful CAD/CAM packages in industry. This is also a great potential for industry application. The case study presented here is a concrete example but the modelling methods and techniques can be applied for other spatial cams with cylindrical rollers when the angular input/output are known. The result of this study is very useful in terms of modelling and manufacturing globoidal cam.

6. Acknowledgement

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Appendix

α	β
0.00	0.00000000
0.20	0.00000000
0.40	0.00000000
0.80	0.00000000
0.80	0.00000000
1.00	0.00000000
….	…
104.60	0.00000000
104.80	0.00000000
105.00	0.00000000
105.20	0.00000680
105.40	0.00005418
105.60	0.00018212
105.80	0.00042995
106.00	0.00083638
106.20	0.00143945
106.40	0.00227659
106.60	0.00338459
106.80	0.00479962
…	…
146.40	22.97922791
146.60	23.18530279
146.80	23.39136475
147.00	23.59739548
147.20	23.80337666
147.40	24.00928999
147.60	24.21511717
147.80	24.42083990
148.00	24.62643991
148.20	24.83189893
…	…
179.60	44.99616011
179.80	44.99904001
180.00	45.00000000
180.20	44.99904001
180.40	44.99616011
…	…
213.00	23.59739548
213.20	23.39136475
213.40	23.18530279
213.60	22.97922791
213.80	22.77315844
214.00	22.56711268
214.20	22.36110896
214.40	22.15516558
214.60	21.94930085
…	…
253.60	0.00227659
253.80	0.00143945
254.00	0.00083638
254.20	0.00042995
254.40	0.00018212
254.60	0.00005418
254.80	0.00000680
255.00	0.00000000
…	…
359.00	0.00000000
359.20	0.00000000
359.40	0.00000000
359.60	0.00000000
359.80	0.00000000
360.00	0.00000000

Table 1. Example of some selected angular input/output displacements, unit: degree

7. References

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