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Rapid Design through Virtual and Physical Prototyping

Carnegie Mellon University

Introduction to Mechanisms

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6 Cams

6.1 Introduction

6.1.1 A Simple Experiment: What is a Cam?

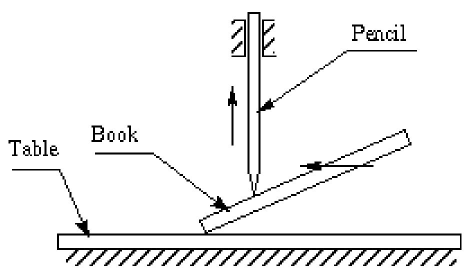

Figure 6-1 Simple Cam experiment

Take a pencil and a book to do an experiment as shown above. Make the book an inclined plane and use the pencil as a slider (use your hand as a guide). When you move the book smoothly upward, what happens to the pencil? It will be pushed up along the guide. By this method, you have transformed one motion into another motion by a very simple device. This is the basic idea of a cam. By rotating the cams in the figure below, the bars will have either translational or oscillatory motion.

6.1.2 Cam Mechanisms

The transformation of one of the simple motions, such as rotation, into any other motions is often conveniently accomplished by means of a **cam mechanism** A cam mechanism usually consists of two moving elements, the cam and the follower, mounted on a fixed frame. Cam devices are versatile, and almost any arbitrarily-specified motion can be obtained. In some instances, they offer the simplest and most compact way to transform motions.

A ***cam*** may be defined as a machine element having a curved outline or a curved groove, which, by its oscillation or rotation motion, gives a predetermined specified motion to another element called the ***follower*** . The cam has a very important function in the operation of many classes of machines, especially those of the automatic type, such as printing presses, shoe machinery, textile machinery, gear-cutting machines, and screw machines. In any class of machinery in which automatic control and accurate timing are paramount, the cam is an indispensable part of mechanism. The possible applications of cams are unlimited, and their shapes occur in great variety. Some of the most common forms will be considered in this chapter.

6.2 Classification of Cam Mechanisms

We can classify cam mechanisms by the modes of input/output motion, the configuration and arrangement of the follower, and the shape of the cam. We can also classify cams by the different types of motion events of the follower and by means of a great variety of the motion characteristics of the cam profile. (Chen 82)

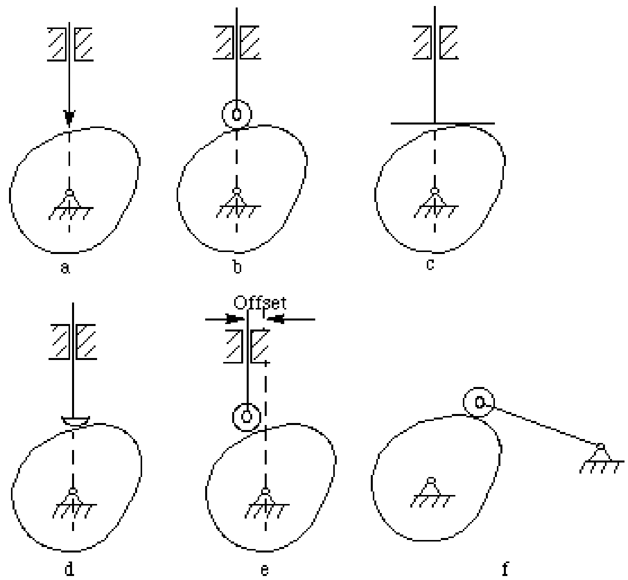

Figure 6-2 Classification of cam mechanisms

4.2.1 Modes of Input/Output Motion

1. Rotating cam-translating follower. (Figure 6-2a,b,c,d,e)
2. Rotating follower (Figure 6-2f):
   The follower arm swings or oscillates in a circular arc with respect to the follower pivot.
3. Translating cam-translating follower (Figure 6-3).
4. Stationary cam-rotating follower:
   The follower system revolves with respect to the center line of the vertical shaft.

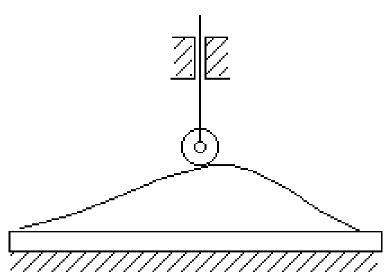

Figure 6-3 Translating cam - translating follower

6.2.1 Follower Configuration

1. **Knife-edge follower** (Figure 6-2a)
2. **Roller follower** (Figure 6-2b,e,f)
3. **Flat-faced follower** (Figure 6-2c)
4. **Oblique flat-faced follower**
5. **Spherical-faced follower** (Figure 6-2d)

6.2.2 Follower Arrangement

1. In-line follower:
   The center line of the follower passes through the center line of the camshaft.
2. Offset follower:
   The center line of the follower does not pass through the center line of the cam shaft. The amount of **offset** is the distance between these two center lines. The offset causes a reduction of the side thrust present in the roller follower.

6.2.3 Cam Shape

1. Plate cam or **disk cam**:
   The follower moves in a plane perpendicular to the axis of rotation of the camshaft. A translating or a swing arm follower must be constrained to maintain contact with the cam profile.
2. **Grooved cam** or closed cam (Figure 6-4):
   This is a plate cam with the follower riding in a groove in the face of the cam.

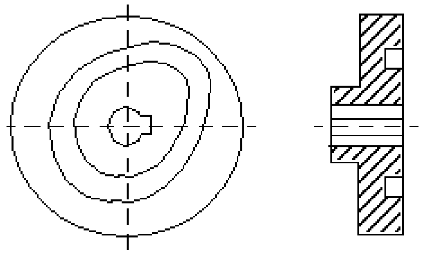

Figure 6-4 Grooved cam

3. **Cylindrical cam** or barrel cam (Figure 6-5a):
   The roller follower operates in a groove cut on the periphery of a cylinder. The follower may translate or oscillate. If the cylindrical surface is replaced by a conical one, a conical cam results.
4. **End cam** (Figure 6-5b):
   This cam has a rotating portion of a cylinder. The follower translates or oscillates, whereas the cam usually rotates. The end cam is rarely used because of the cost and the difficulty in cutting its contour.

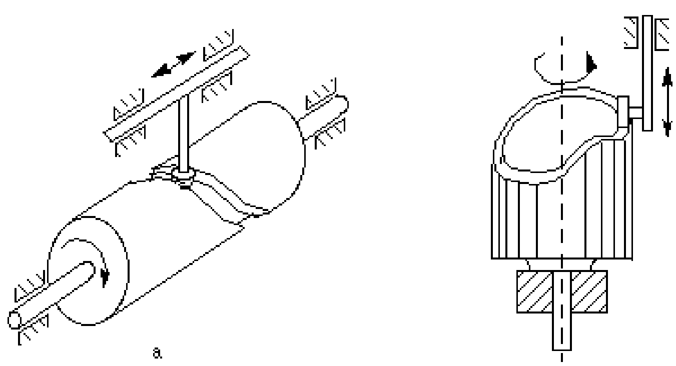

Figure 6-5 Cylindrical cam and end cam

6.2.4 Constraints on the Follower

1. Gravity constraint:
   The weight of the follower system is sufficient to maintain contact.
2. Spring constraint:
   The spring must be properly designed to maintain contact.
3. Positive mechanical constraint:
   A groove maintains positive action. (Figure 6-4 and Figure 6-5a) For the cam in Figure 6-6, the follower has two rollers, separated by a fixed distance, which act as the constraint; the mating cam in such an arrangement is often called a *constant-diameter cam*.

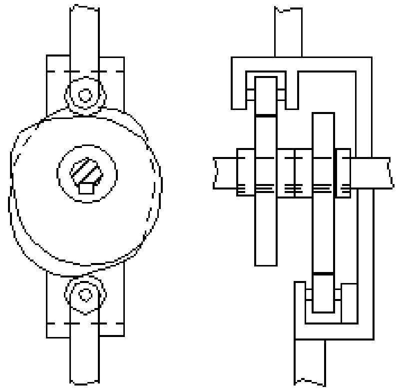

Figure 6-6 Constant diameter cam

A mechanical constraint cam also be introduced by employing a dual or conjugate cam in arrangement similar to what shown in Figure 6-7. Each cam has its own roller, but the rollers are mounted on the same reciprocating or oscillating follower.

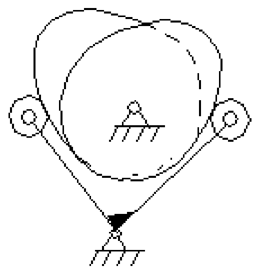

Figure 6-7 Dual cam

6.2.5 Examples in SimDesign

Rotating Cam, Translating Follower

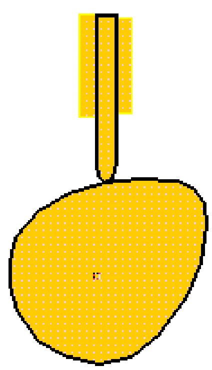

Figure 6-8 SimDesign translating cam

Load the SimDesign file `simdesign/cam.translating.sim`. If you turn the cam, the follower will move. The weight of the follower keeps them in contact. This is called a *gravity constraint* cam.

Rotating Cam/Rotating Follower

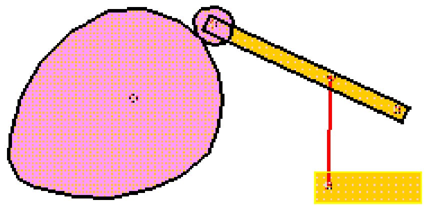

Figure 6-9 SimDesign oscillating cam

The SimDesign file is `simdesign/cam.oscillating.sim`. Notice that a roller is used at the end of the follower. In addition, a spring is used to maintain the contact of the cam and the roller.

If you try to calculate the degrees of freedom (DOF) of the mechanism, you must imagine that the roller is welded onto the follower because turning the roller does not influence the motion of the follower.

6.3 Cam Nomenclature

Figure 6-10 illustrates some cam nomenclature:

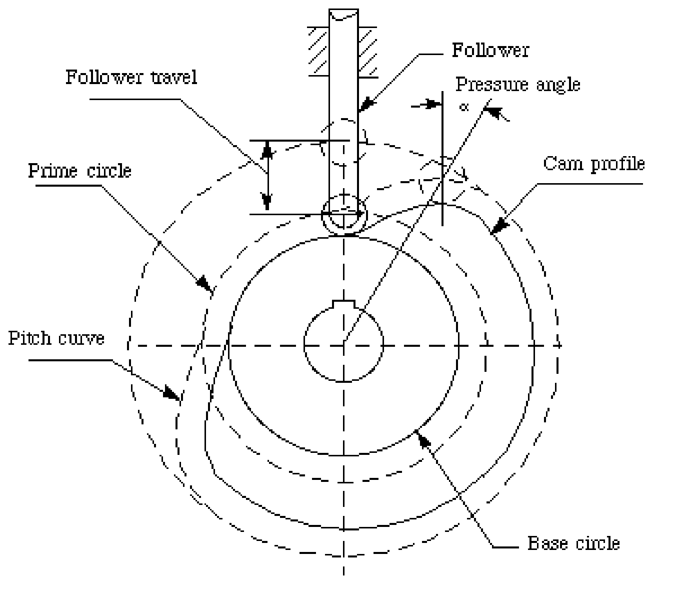

Figure 6-10 Cam nomenclature

- **Trace point**: A theoretical point on the follower, corresponding to the point of a fictitious *knife-edge follower*. It is used to generate the *pitch curve*. In the case of a *roller follower*, the trace point is at the center of the roller.
- **Pitch curve**: The path generated by the trace point at the follower is rotated about a stationary cam.
- **Working curve**: The working surface of a cam in contact with the follower. For the *knife-edge follower* of the plate cam, the *pitch curve* and the *working curves* coincide. In a *close or grooved cam* there is an *inner profile* and an *outer working curve*.
- **Pitch circle**: A circle from the cam center through the pitch point. The pitch circle radius is used to calculate a cam of minimum size for a given *pressure angle*.
- **Prime circle** (**reference circle**): The smallest circle from the cam center through the pitch curve.
- **Base circle**: The smallest circle from the cam center through the cam profile curve.
- **Stroke** or **throw**:The greatest distance or angle through which the follower moves or rotates.
- **Follower displacement**: The position of the follower from a specific zero or rest position (usually its the position when the *f* ollower contacts with the *base circle* of the cam) in relation to time or the rotary angle of the cam.
- **Pressure angle**: The angle at any point between the normal to the pitch curve and the instantaneous direction of the follower motion. This angle is important in cam design because it represents the steepness of the cam profile.

6.4 Motion events

When the cam turns through one motion cycle, the follower executes a series of events consisting of rises, dwells and returns. **Rise** is the motion of the follower away from the cam center, **dwell** is the motion during which the follower is at rest; and **return** is the motion of the follower toward the cam center.

There are many follower motions that can be used for the rises and the returns. In this chapter, we describe a number of basic curves.

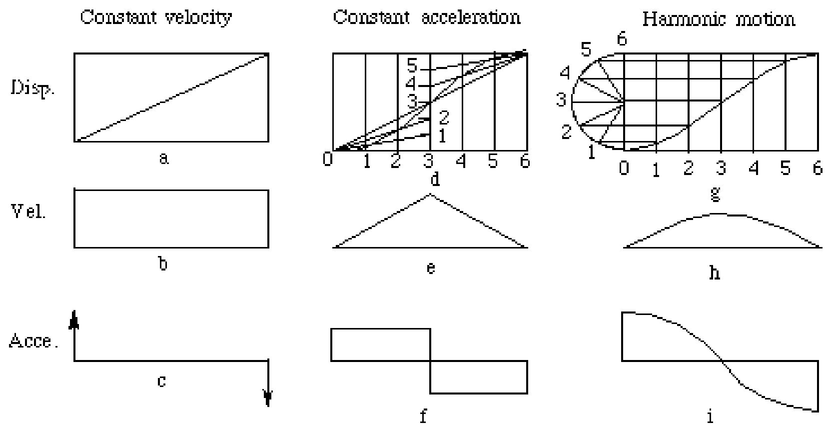

Figure 6-11 Motion events

Notation

ϕ: The rotary angle of the cam, measured from the beginning of the motion event;
β: The range of the rotary angle corresponding to the motion event;
h : The stoke of the motion event of the follower;
S : Displacement of the follower;
V : Velocity of the follower;
A : Acceleration of the follower.

6.4.1 Constant Velocity Motion

If the motion of the follower were a straight line, Figure 6-11a,b,c, it would have equal displacements in equal units of time, *i.e.*, uniform velocity from the beginning to the end of the stroke, as shown in b. The acceleration, except at the end of the stroke would be zero, as shown in c. The diagrams show abrupt changes of velocity, which result in large forces at the beginning and the end of the stroke. These forces are undesirable, especially when the cam rotates at high velocity. The *constant velocity motion* is therefore only of theoretical interest.

$$S(\varphi) = h\frac{\varphi}{\beta}$$
$$V(\varphi) = \frac{h}{\beta}$$
$$A(\varphi) = 0$$

(6-1)

6.4.2 Constant Acceleration Motion

Constant acceleration motion is shown in Figure 6-11d, e, f. As indicated in e, the velocity increases at a uniform rate during the first half of the motion and decreases at a uniform rate during the second half of the motion. The acceleration is constant and positive throughout the first half of the motion, as shown in f, and is constant and negative throughout the second half. This type of motion gives the follower the smallest value of maximum acceleration along the path of motion. In high-speed machinery this is particularly important because of the forces that are required to produce the accelerations.

When

$0 \le \varphi \le \frac{\beta}{2}$,

$$S(\varphi) = 2h\frac{\varphi^2}{\beta^2}$$
$$V(\varphi) = \frac{4h}{\beta^2}\varphi$$
$$A(\varphi) = \frac{4h}{\beta^2}$$

(6-2)

When
$\frac{\beta}{2} \le \varphi \le \beta$,

$$S(\varphi) = h - \frac{2h}{\beta^2}(\beta - \varphi)^2$$
$$V(\varphi) = \frac{4h}{\beta}\left(1 - \frac{\varphi}{\beta}\right)$$
$$A(\varphi) = -\frac{4h}{\beta^2}$$

(6-3)

6.4.3 Harmonic Motion

A cam mechanism with the basic curve like g in Figure 6-7g will impart *simple harmonic motion* to the follower. The velocity diagram at h indicates smooth action. The acceleration, as shown at i, is maximum at the initial position, zero at the mid-position, and negative maximum at the final position.

$$S(\varphi) = \frac{h}{2}\left(1 - \cos\frac{\pi\varphi}{\beta}\right)$$
$$V(\varphi) = \frac{h\pi}{2\beta}\sin\frac{\pi\varphi}{\beta}$$
$$A(\varphi) = \frac{h\pi^2}{2\beta^2}\cos\frac{\pi\varphi}{\beta}$$

(6-4)

6.5 Cam Design

The translational or rotational displacement of the follower is a function of the rotary angle of the cam. A designer can define the function according to the specific requirements in the design. The motion requirements, listed below, are commonly used in cam profile design.

6.5.1 Disk Cam with Knife-Edge Translating Follower

Figure 6-12 is a skeleton diagram of a disk cam with a knife-edge translating follower. We assume that the cam mechanism will be used to realize the displacement relationship between the rotation of the cam and the translation of the follower.

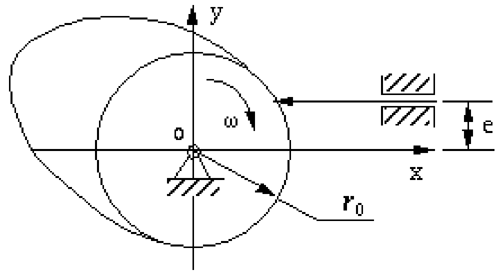

Figure 6-12 A Skeleton Diagram of disk cam with knife-edge translation

Below is a list of the essential parameters for the evaluation of these types of cam mechanisms. However, these parameters are adequate only to define a knife-edge follower and a translating follower cam mechanism.

Parameters:

r_o: The radius of the base circle;
e: The offset of the follower from the rotary center of the cam. Notice: it could be negative.
s: The displacement of the follower which is a function of the rotary angle of the cam -- Φ.
IW: A parameter whose absolute value is 1. It represents the turning direction of the cam. When the cam turns clockwise: *IW=+1*, otherwise: *IW=-1*.

Cam profile design principle:

The method termed inversion is commonly used in cam profile design. For example, in a disk cam with translating follower mechanism, the follower translates when the cam turns. This means that the relative motion between them is a combination of a relative turning motion and a relative translating motion. Without changing this feature of their relative motion, imagine that the cam remains fixed. Now the follower performs both the relative turning and translating motions. We have inverted the mechanism.

Furthermore, imagine that the knife-edge of the follower moves along the fixed cam profile in the inverted mechanism. In other words, the knife edge of the follower draws the profile of the cam. Thus, the problem of designing the cam profile becomes a problem of calculating the trace of the knife edge of the follower whose motion is the combination of the relative turning and the relative translating.

Design equations:

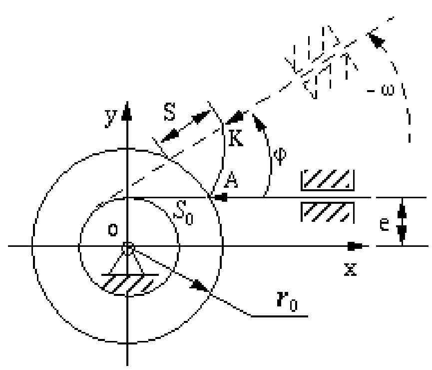

Figure 6-13 Profile design of translating cam follower

In Figure 6-13, only part of the cam profile *AK* is displayed. Assume the cam turns clockwise. At the beginning of motion, the knife edge of the follower contacts the point of intersection *A* of the base circle and the cam profile. The coordinates of *A* are (*So, e*), and *So* can be calculated from equation $S_0 = \sqrt{r_0^2 - e^2}$

Suppose the displacement of the follower is *S* when the angular displacement of the cam is Φ. At this moment, the coordinates of the knife edge of the follower should be (*So* + *S, e*).

To get the corresponding position of the knife edge of the follower in the inverted mechanism, turn the follower around the center of the cam in the reverse direction through an angle of Φ. The knife edge will be inverted to point *K*, which corresponds to the point on the cam profile in the inverted mechanism. Therefore, the coordinates of point *K* can be calculated with the following equation:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos(IW \cdot \varphi) & -\sin(IW \cdot \varphi) \\ \sin(IW \cdot \varphi) & \cos(IW \cdot \varphi) \end{bmatrix} \begin{bmatrix} S_0 + S \\ e \end{bmatrix} \tag{6-5}$$

Note:

- The offset *e* is negative if the follower is located below the *x* axis.
- When the rotational direction of the cam is clockwise: *IW* = *+1*, otherwise: *IW* = *-1*.

6.5.2 Disk Cam with Oscillating Knife-Edge Follower

Suppose the cam mechanism will be used to make the knife edge oscillate. We need to compute the coordinates of the cam profile that results in the required motion of the follower.

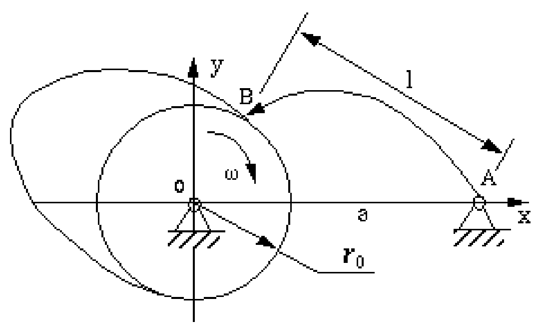

Figure 6-14 Disk cam with knife-edge oscillating follower

The essential parameters in this kind of cam mechanisms are given below.

r_o: The radius of the base circle;
a: The distance between the pivot of the cam and the pivot of the follower.
l: The length of the follower which is a distance from its pivot to its knife edge.
Ψ: The angular displacement of the follower which is a function of the rotary angle of the cam -- Φ.
IP: A parameter whose absolute value is 1. It represents the location of the follower. When the follower is located above the *x* axis: *IP=+1*, otherwise: *IP=-1*.
IW: A parameter whose absolute value is 1. It represents the turning direction of the cam. When the cam turns clockwise: *IW=+1*, otherwise: *IW=-1*.

Cam profile design principle

The fundamental principle in designing the cam profiles is still inversion, similar to that that for designing other cam mechanisms, (*e.g.*, the translating follower cam mechanism). Normally, the follower oscillates when the cam turns. This means that the relative motion between them is a combination of a relative turning motion and a relative oscillating motion. Without changing this feature of their relative motion, let the cam remain fixed and the follower performs both the relative turning motion and oscillating motion. By imagining in this way, we have actually inverted the mechanism.

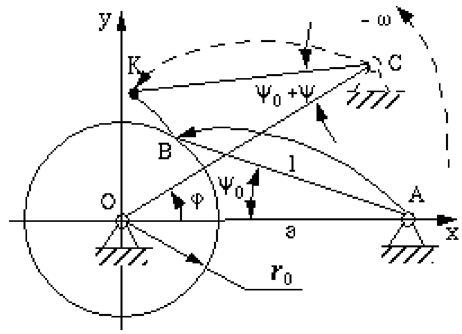

Figure 6-15 Cam profile design for a rotating follower

In Figure 6-15, only part of the cam profile *BK* is shown. We assume that the cam turns clockwise.

At the beginning of motion, the knife edge of the follower contacts the point of intersection (*B*) of the base circle and the cam profile. The initial angle between the follower (*AB*) and the line of two pivots (*AO*) is $\Psi 0$. It can be calculated from the triangle *OAB*.

When the angular displacement of the cam is Φ, the oscillating displacement of the follower is Ψ which measures from its own initial position. At this moment, the angle between the follower and the line passes through two pivots should be $\Psi+\Psi 0$.

The coordinates of the knife edge at this moment will be

$$(a - l\cos[IP(\psi+\psi_0)],\, l\sin[IP(\psi+\psi_0)])$$

(6-6)

To get the corresponding knife-edge of the follower in the inverted mechanism, simply turn the follower around the center of the cam in the reverse direction of the cam rotation through an angle of Φ. The knife edge will be inverted to point *K* which corresponds to the point on the cam profile in the inverted mechanism. Therefore, the coordinates of point *K* can be calculated with the following equation:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos(IW\cdot\varphi) & -\sin(IW\cdot\varphi) \\ \sin(IW\cdot\varphi) & \cos(IW\cdot\varphi) \end{bmatrix} \begin{bmatrix} a - l\cos[IP(\psi+\psi_0)] \\ l\sin[IP(\psi+\psi_0)] \end{bmatrix}$$

(6-7)

Note:

- When the initial position of the follower is above the *x* axis, *IP = +1*, otherwise: *IP = -1*.
- When the rotary direction of the cam is clockwise: *IW = +1*, otherwise: *IW = -1*.

6.5.3 Disk Cam with Roller Follower

Additional parameters:

- *r*: the radius of the roller.
- *IM*: a parameter whose absolute value is 1, indicating which envelope curve will be adopted.
- *RM*: inner or outer envelope curve. When it is an inner envelope curve: *RM=+1*, otherwise: *RM=-1*.

Design principle:

The basic principle of designing a cam profile with the inversion method is still used. However, the curve is not directly generated by inversion. This procedure has two steps:

1. Imagine the center of the roller as a knife edge. This concept is important in cam profile design and is called the trace

point) of follower. Calculate the pitch curve *aa*, that is, the trace of the pitch point in the inverted mechanism.
2. The cam profile *bb* is a product of the enveloping motion of a series of rollers.

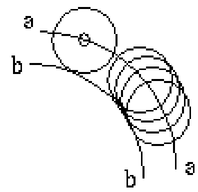

Figure 6-16 The trace point of the follower on a disk cam

Design equations:

The problem of calculating the coordinates of the cam profile is the problem of calculating the tangent points of a sequence of rollers in the inverted mechanism. At the moment shown Figure 6-17, the tangent point is *P* on the cam profile.

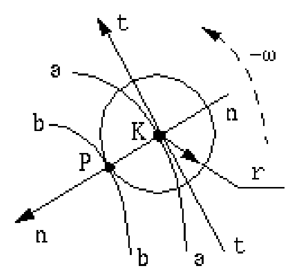

Figure 6-17 The tangent point, P, of a roller to the disk cam

The calculation of the coordinates of the point *P* has two steps:

1. Calculate the slope of the tangent *tt* of point *K* on pitch curve, *aa*.
2. Calculate the slope of the normal *nn* of the curve *aa* at point *K*.

Since we have already have the coordinates of point *K:* (*x, y*), we can express the coordinates of point *P* as

$$\begin{cases} x_p = x - IW \cdot RM \cdot r \cdot \dfrac{dy/d\varphi}{\sqrt{(dx/d\varphi)^2 + (dy/d\varphi)^2}} \\ y_p = y + IW \cdot RM \cdot r \cdot \dfrac{dx/d\varphi}{\sqrt{(dx/d\varphi)^2 + (dy/d\varphi)^2}} \end{cases} \tag{6-8}$$

Note:

- When the rotary direction of the cam is clockwise: *IW = +1*, otherwise: *IW = -1*.
- when the envelope curve (cam profile) lies inside the pitch curve: *RM = +1*, otherwise: *RM = -1*.

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