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Modeling Concave Globoidal Cam with Swinging Roller Follower: A Case Study

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Abstract**—**This paper describes a computer-aided design for design of the concave globoidal cam with cylindrical rollers and swinging follower. Four models with different modeling methods are made from the same input data. The input data are angular input and output displacements of the cam and the follower and some other geometrical parameters of the globoidal cam mechanism. The best cam model is the cam which has no interference with the rollers when their motions are simulated in assembly conditions. The angular output displacement of the follower for the best cam is also compared with that of in the input data to check errors. In this study, Pro/ENGINEER® Wildfire 2.0 is used for modeling the cam, simulating motions and checking interference and errors of the system.

Keywords**—**Globoidal cam, sweep, pitch surface, modeling.

I. 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. Up to now, lots of efforts have been made in finding the way to describe the complicated surfaces of the globoidal cam. Yan and Chen [7[, [8] derived mathematical expression for the surface geometry of the globoidal cam with cylindrical rollers and hyperboloid rollers based on coordinate transformation, differential geometry, and theory of conjugate surfaces. To analyze the transmission error and to synthesize the tolerances, Cheng [1] also made the geometric mathematical models of the globoidal cam surface by the conjugating theory. Tsay and Lin [6] studied the globoidal cam with conical rollers. From machining point of view, they presented the sweep surfaces for the cam surfaces by means of the sweep surfaces of the tool paths. Yuan et al. [2] used computer to develop a package, which is a combination of AutoCAD R14, 3D Studio Max, and VBA, to generate the surfaces of the roller gear cam. In addition, many researchers have studied on other aspects of the globoidal cam such as the contact between cam surfaces and the rollers, dynamics, machining on four-axis or five-axis machine tools, etc… In this study, to illustrate the cam surfaces from angular input and output displacements, some modeling methods are presented.

II. Theoretical Background

The globoidal cam rotates about its axis and the cam drives a roller follower. 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. The cam of this type is either convex or concave. The second one has one or more ribs on its surface. This type is also called roller gear drive or Ferguson drive [5]. The two surfaces of the rib always contact with the rollers (cylindrical or conical) of the follower. This type has two subtypes: concave globoidal cam with an oscillating follower and indexing globoidal cam with a turret follower (Fig. 1). 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 cam. In this study, the single thread-type is the globoidal cam that we will deal with.

Fig. 2 illustrates the geometrical relationships between a concave globoidal cam with a oscillating follower. In this fig., 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.

Following are some parameters related to globoidal cam-follower system [3], [4].

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 $\beta = f(\alpha)$, [2].

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

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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.

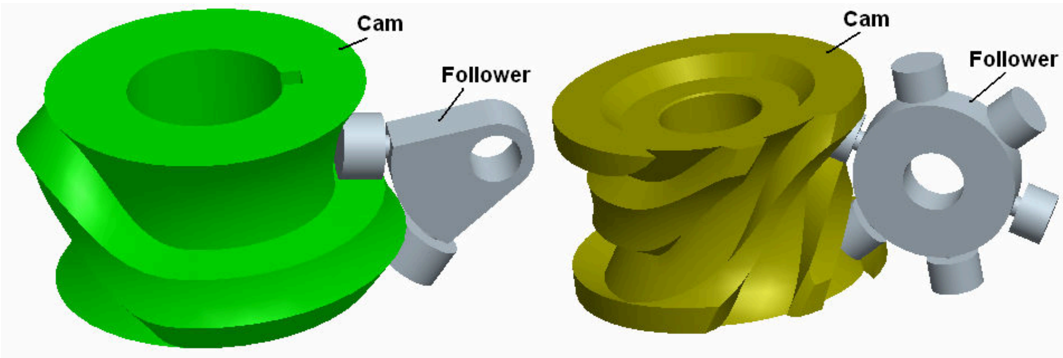
R - perpendicular distance from cam axis to the pitch point, expressed as

$$R = C - F.\cos(\beta^1) \quad (1)$$

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

$$h = F.\sin(\beta^1) \quad (2)$$

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.



(a) Oscillating follower (b) Indexing turret follower

Fig. 1 Globoidal cam - thread type

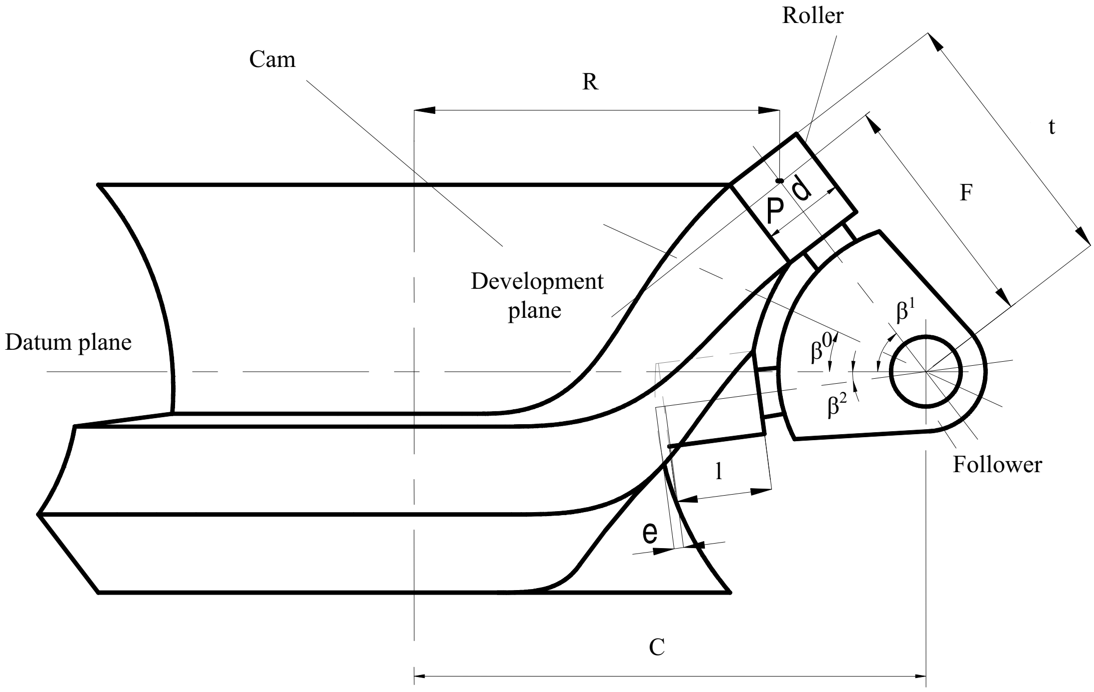


Fig. 2 Globoidal cam- oscillating follower arrangement

III. Modeling Methods

The globoidal cam can be modeled by using CAD software. In this study, Pro/Engineer® Wildfire 2.0 is used. There are two methods to model the globoidal cam: surface-based modeling and solid-based modeling. In the first method, all surfaces of the cam are first modeled and then the surface model is converted to solid.

A. Surface-Based Modeling

In a globoidal cam-follower system, when the follower rotates, the locus of roller axis will generate a ruled surface (pitch curved surface) in space [6]. The two axes of two rollers in this case study will generate two pitch curved surfaces. The globoidal cam surfaces can be obtained from the pitch surfaces by offsetting them a distance that is equal to the radius of the roller. There are several ways to get the pitch surface. The following are three ways to model the pitch surface.

Model 1:

Sweep a straight line that is collinear with the roller axis. The two end points of this line must lie on two curves. 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. The other curve is a three-dimensional (3D) curve and it is the origin trajectory. 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 can be calculated in the cylindrical coordinate system as

α_j - input angular displacement

$$h_j^i = F.\sin\beta_j^i \tag{3}$$

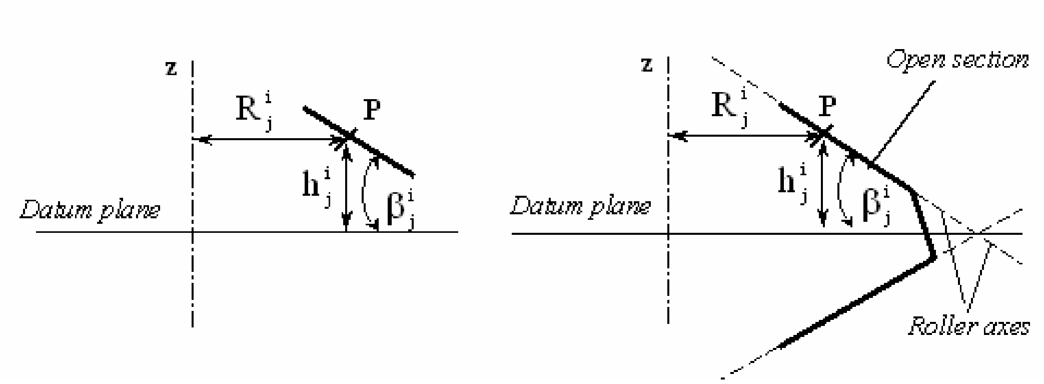
$$R_j^i = C - F.\cos\beta_j^i \tag{4}$$

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

Model 2:

Sweep a straight line with three constraints: (i) the origin trajectory is a circle in the datum plane and its symmetric axis coincides with the cam axis, (ii) the angle between this line and the datum plane varies when the cam rotates and its value is β_j^i (Fig. 3(a)), (iii) the coordinates of a point on this line satisfies formulas (3) and (4) above.

The origin trajectory can be a circle that is the intersection between the datum plane and the body surface of the cam. Datum graphs and sketcher relations are used to fulfill the constraints (ii) and (iii) above [9]. The same procedures are done to get the two pitch surfaces of the cam.



(a) (b)

Fig. 3 Constrains for model 2 and model 3

Model 3:

Sweep an "opened 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. Similarly, the constraints that are used to make model 2 (Fig. 3(b)) are also used here.

In this method, first, the body surface is modeled, and then the two pitch surfaces are done. Make one or two offsets from the pitch surfaces to get the cam surfaces. In model 2, a boundary surface can be added to unite the two cam surfaces if they do not intersect each other. After that, the body surface, the cam surfaces and the boundary surface are merged together. The united surface will be solidified to become a solid. Last, perform some cuts to get the desired cam.

B. *Solid-based modeling*

An endmill 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 the motion 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 cam surface. The following is one way to get the cam surface.

Model 4:

Cut the bank by a rectangular section 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 is arbitrary providing that it is longer than the length of the roller plus the clearance e (Fig. 2).
2) Sweep this section and the axis of the section 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 for model 1 can be applied here.
3) This section plane is always normal to the origin trajectory.

In this method, first a solid body is modeled. Then, two cuts are performed to get the cam surfaces. Last, some cuts are done to get the desired cam.

IV. Application Example

A. Input Data and Pre-Calculations

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. To observe easily, the relationship between the angular input and output displacements is showed in Fig. 4. Some selected displacements are presented in the appendix. Following are some other parameters of the system, which are showed in Fig. 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 with.

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

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

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.

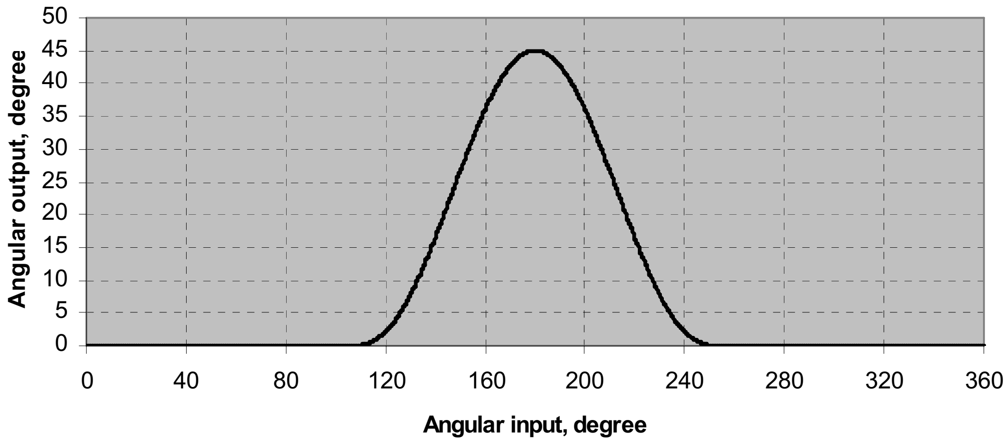


Fig. 4 Angular input/output displacement

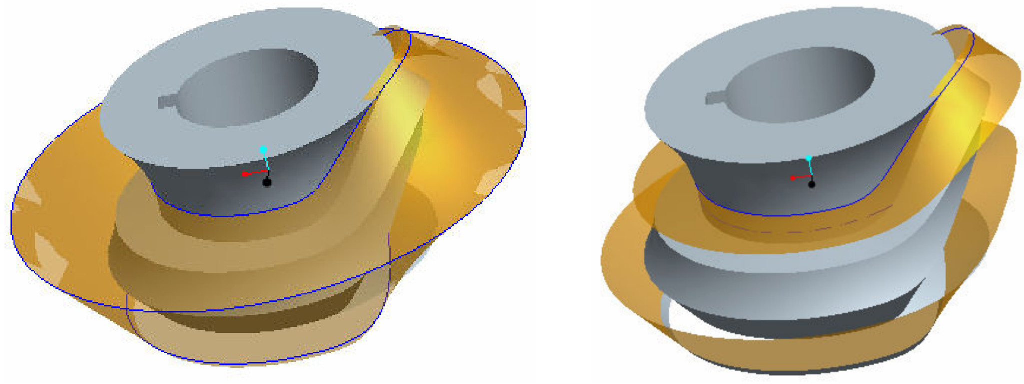
B. Modeling Results and Checking Interference

In Fig. 5 are four types of the cam modeled from preceding data. In this fig., the pitch surfaces are in transparent state to see the cam surfaces easily. All cams look great and similar. To choose the best model, the interference between the cam and the roller must be checked.

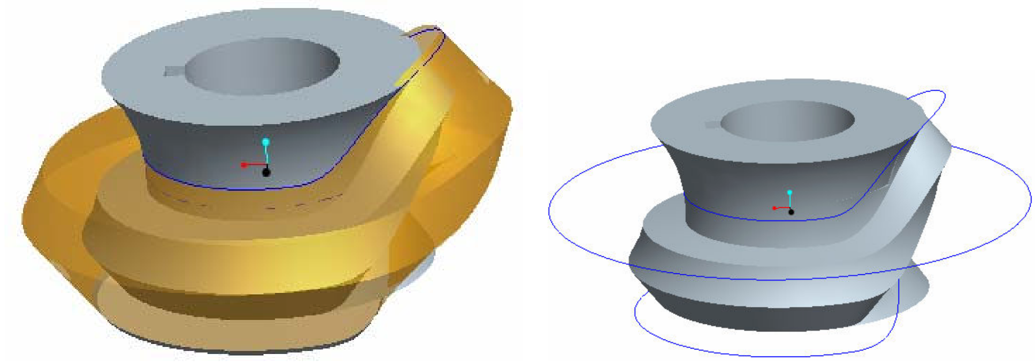
In order to check the interference, first, an assembly of the cam and the follower is made. After that, use the Mechanism Design module to define the geometrical relationships of the system, make it move and analyze its motion also. Last, use a kinematics analysis to obtain information on interference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

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. This 3D curve is available on the model 1 and model 4. This curve must be drawn on the others also.

Among the four models, model 1 has no interference between the cam and the roller when the cam rotates one revolution, while models 2, 3 and 4 have interferences (Fig. 6). Model 2 and 3 have 51 and 35 positions of interference, respectively. Model 4 has a lot of positions where interferences occur. 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 3, model 4 has bigger interference volumes and they can be seen in the graphic window. The result is that model 1 is the best one. The model 2 can also be a good one if the part accuracy is set from 0.0012 (the default value) to 0.0005. In this case, there is no interference between the cam and the roller.

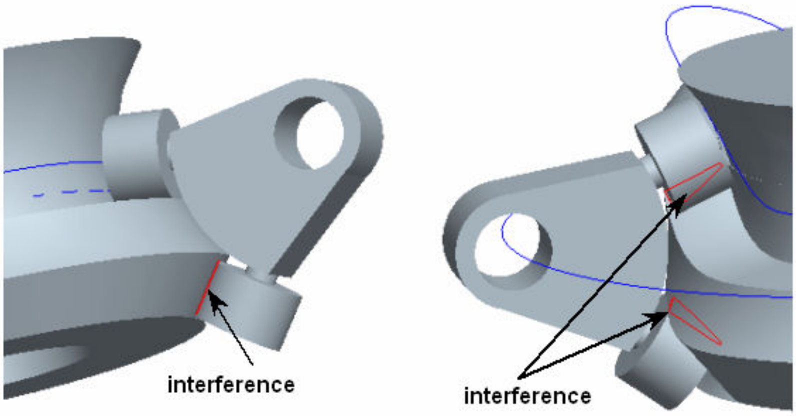


(a) Pitch surfaces and cam – model 1 (b) Pitch surfaces and cam – model 2



(c) Pitch surfaces and cam – model 3 (d) Cam - model 4

Fig. 5 Four models of globoidal cam



(a) Model 2 (and 3) (b) Model 4

Fig. 6 Interferences (in red colour) occur between components

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The clearances in assembly between cam surfaces of model 1 and their rollers must be checked to ensure that they are small enough. If these clearances are large, the errors of output angular displacements will be large, too. These clearances can be measured in assembly standard mode or in mechanism mode. Some selected errors are presented in Table I in the appendix. In general, these clearances are always less than 0.2 micrometer. In one revolution of the cam, the biggest gaps are on the rise and return periods. These gaps also cause errors in the output angular displacements but these errors are very small and they can be ignored.

In Mechanism Design module, the angular output displacements of the follower can be measured and the result can be exported to Microsoft Excel. By comparing the measured angular output displacements with the required input data, the errors of the model will be evaluated. In general, there are errors in rotation angles of the follower when the cam moves a full revolution. These errors vary from -0.000,000,42 degree to 0.000,000,43 degree (see Table II in the appendix). They are very small and can be omitted.

V. CONCLUSION

In this study, four models of the concave globoidal cam are developed from the same input data by using the software Pro/Engineer® Wildfire 2.0. The result is that the model, which its pitch surfaces are obtained by sweeping straight lines along two curves (loci of two points on roller axes), is the best one. With this model, no interference between components is found when the system is working and the errors of angular rotation of the follower are very small. This is a real example but its modeling procedures can be applied for other situations when the angular input/output are known. The result of this study is very useful in terms of modeling and manufacturing globoidal cam.

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APPENDIX

TABLE I
EXAMPLE OF SOME SELECTED CLEARANCES BETWEEN CAM SURFACES AND ROLLERS

α [deg]	e_1[mm]	e_2 [mm]	α [deg]	e_1 [mm]	e_2 [mm]
0	0.0000000020	0.0000000013	195	0.0000000000	0.0001421750
15	0.0000000049	0.0000000053	210	0.0000000000	0.0000000000
30	0.0000000049	0.0000000053	225	0.0000000000	0.0000000000
45	0.0000000049	0.0000000053	240	0.0001681920	0.0000000000
60	0.0000000048	0.0000000051	255	0.0000992641	0.0000000000
75	0.0000000048	0.0000000051	270	0.0000000048	0.0000000051
90	0.0000000048	0.0000000051	285	0.0000000048	0.0000000051
105	0.0000992641	0.0000000000	300	0.0000000048	0.0000000051
120	0.0001681920	0.0000000000	315	0.0000000049	0.0000000053
135	0.0000000000	0.0000000000	330	0.0000000049	0.0000000053
150	0.0000000000	0.0000000000	345	0.0000000049	0.0000000053
165	0.0000000000	0.0001421750	360	0.0000000020	0.0000000013
180	0.0000003888	0.0000003815			

Note: e_1: clearance between cam surface and upper roller (model 1).
e_2: clearance between cam surface and lower roller (model 1).

TABLE II
EXAMPLE OF SOME SELECTED ANGULAR INPUT/OUTPUT DISPLACEMENTS, UNIT: DEGREE

α	β	β*	ε	α	β	β*	ε
0.00	0.00000000	8.17575E-08	0.00000008	179.60	44.99616011	44.99616012	0.00000001
0.20	0.00000000	-1.70511E-10	0.00000000	179.80	44.99904001	44.99904002	0.00000001
0.40	0.00000000	-1.70083E-10	0.00000000	180.00	45.00000000	44.99999999	-0.00000001
….	…	…	…	180.20	44.99904001	44.99904001	0.00000000
105.00	0.00000000	-1.54018E-10	0.00000000	180.40	44.99616011	44.9961601	-0.00000001
105.20	0.00000680	6.79984E-06	0.00000000	…	…	…	…
105.40	0.00005418	5.41793E-05	0.00000000	213.00	23.59739548	23.59739506	-0.00000042
…	…	…	…	213.20	23.39136475	23.39136433	-0.00000042
147.00	23.59739548	23.5973959	0.00000042	213.40	23.18530279	23.18530237	-0.00000042
147.20	23.80337666	23.80337707	0.00000041	213.60	22.97922791	22.97922749	-0.00000042
147.40	24.00928999	24.00929042	0.00000043	213.80	22.77315844	22.77315802	-0.00000042
147.60	24.21511717	24.21511759	0.00000042	214.00	22.56711268	22.56711226	-0.00000042
147.80	24.42083990	24.42084032	0.00000042	…	…	…	…
148.00	24.62643991	24.62644033	0.00000042	359.60	0.00000000	-1.7008E-10	0.00000000
148.20	24.83189893	24.83189935	0.00000042	359.80	0.00000000	-1.70081E-10	0.00000000
…	…	…	…	360.00	0.00000000	8.17575E-08	0.00000008

Note: β: theoretic angular output displacement of the follower
β*: real angular output displacement of the follower (model 1).
ε: error of the angular output displacement of the follower (model 1).

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