April 13, 1965 F. B. BURT 3,177,774

METHOD FOR GENERATING CAM SURFACES

Original Filed Jan. 23, 1957 4 Sheets-Sheet 1

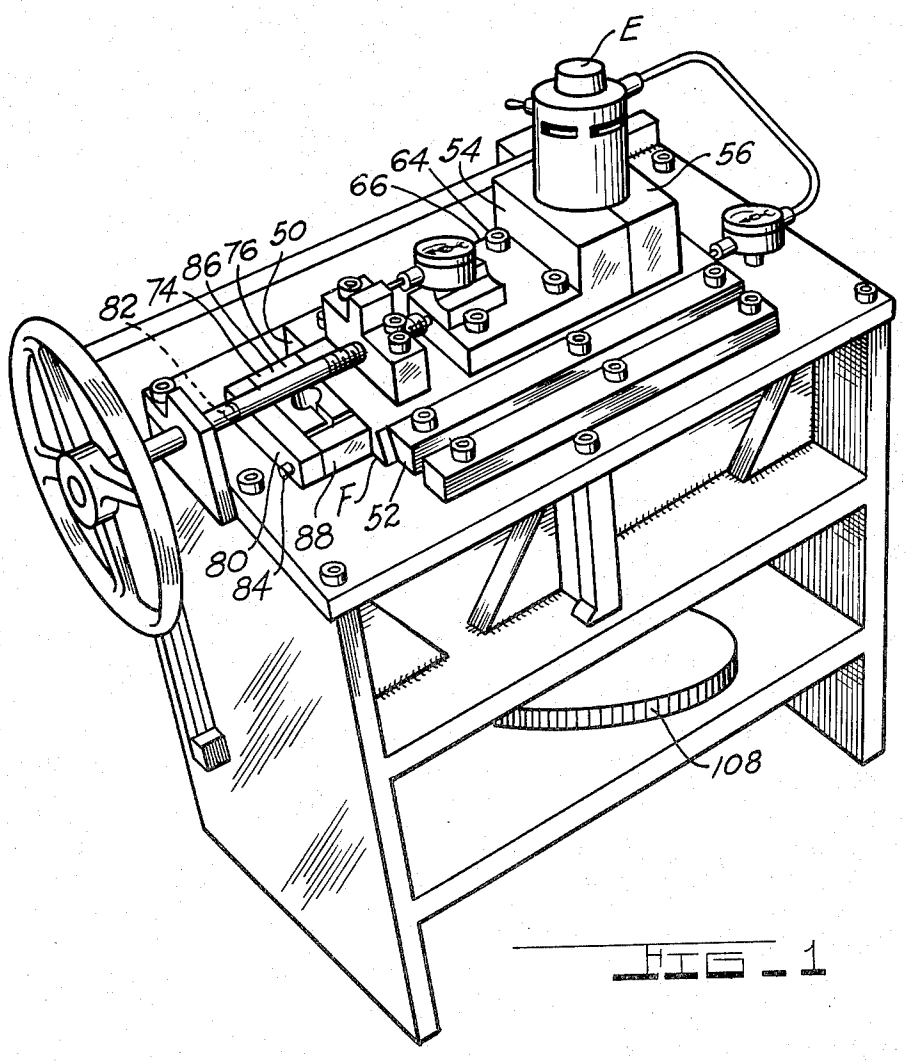


FIG. 1

INVENTOR.
FARLOW B. BURT.
BY
Richard H. Seib
ATTORNEY

April 13, 1965 F. B. BURT 3,177,774

METHOD FOR GENERATING CAM SURFACES

Original Filed Jan. 23, 1957 4 Sheets-Sheet 2

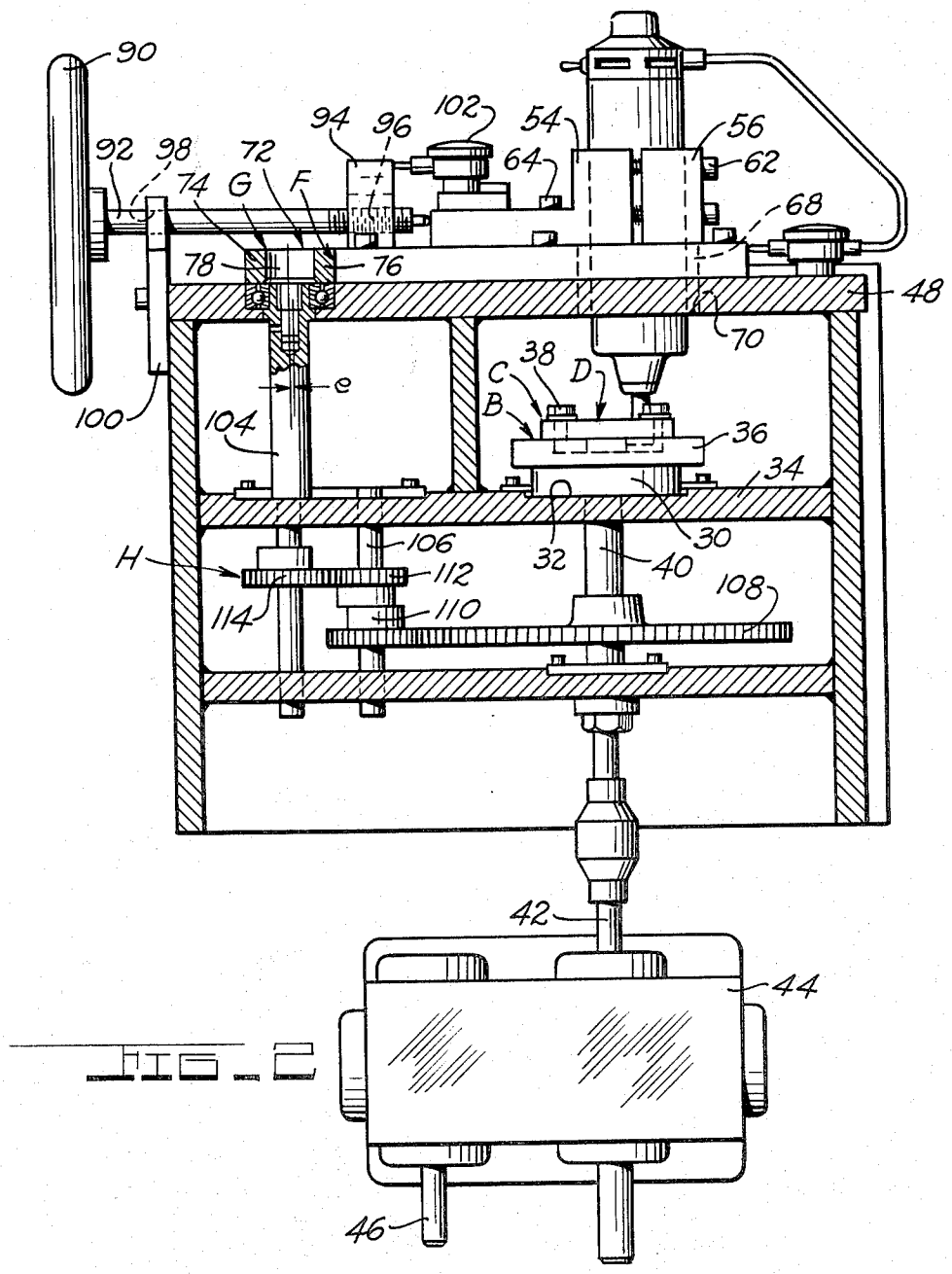


FIG. 2

INVENTOR.
FARLOW B. BURT.
BY
Richard H. Geib
ATTORNEY.

April 13, 1965 F. B. BURT 3,177,774

METHOD FOR GENERATING CAM SURFACES

Original Filed Jan. 23, 1957 4 Sheets-Sheet 3

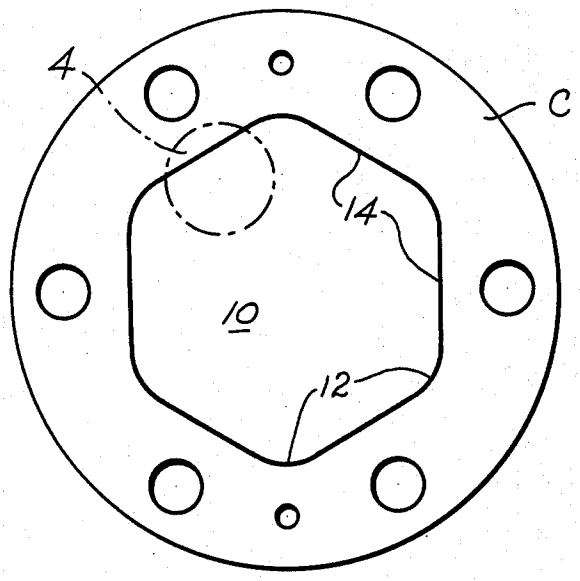


FIG. 3

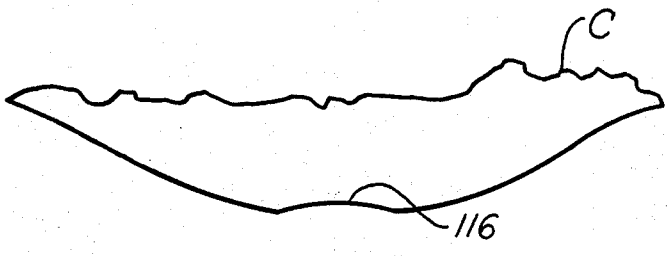


FIG. 4

INVENTOR.
FARLOW B. BURT.
BY
Richard G. Geib
ATTORNEY

April 13, 1965 F. B. BURT 3,177,774

METHOD FOR GENERATING CAM SURFACES

Original Filed Jan. 23, 1957 4 Sheets-Sheet 4

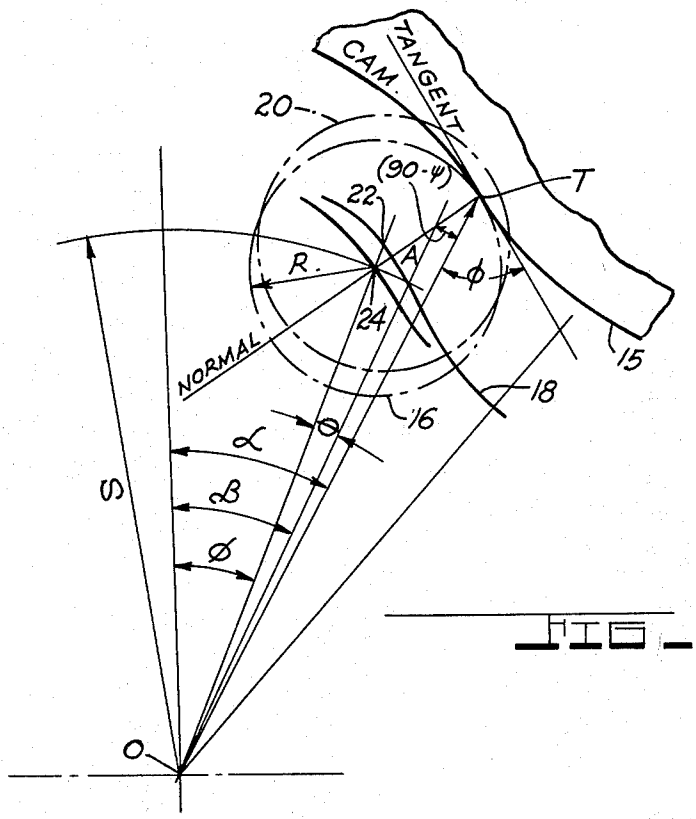


FIG. 5

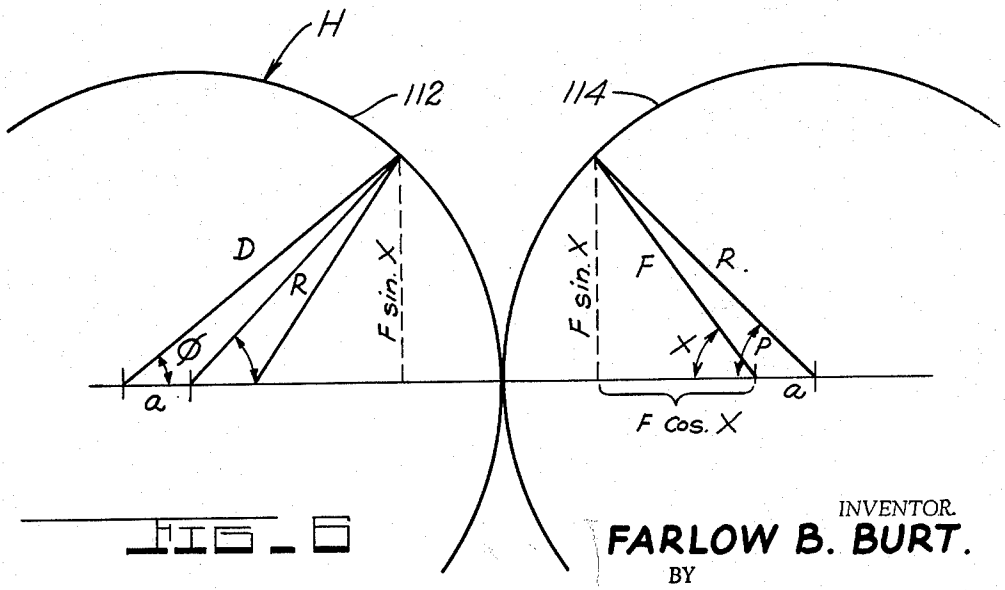


FIG. 6

INVENTOR.
FARLOW B. BURT.
BY
Richard G. Geib
ATTORNEY

United States Patent Office 3,177,774 Patented Apr. 13, 1965

3,177,774

METHOD FOR GENERATING CAM SURFACES

Farlow B. Burt, Winter Park, Fla., assignor to The Bendix Corporation, South Bend, Ind., a corporation of Delaware

Application Mar. 28, 1960, Ser. No. 18,113, which is a division of application Ser. No. 635,747, Jan. 23, 1957, now Patent No. 2,958,264, dated Nov. 1, 1960. Divided and this application July 6, 1962, Ser. No. 208,141

3 Claims. (Cl. 90—11)

The present invention relates to method for accurately forming cam surfaces of the type having continuously repeating sections spaced about an axis of rotation; and to a particular shape of cam surface which can be accurately produced very economically by further refinements in this method. The present invention is a division of my copending application Serial No. 18,113, filed March 28, 1960, now abandoned, which in turn is a division of Patent No. 2,958,264, issued November 1, 1960.

An object of the present invention is the provision of a new and improved method of forming cam surfaces of the above described type.

Another object of the invention is the provision of a new and improved method of generating a cam surface in which a rotatable cutting element is positioned radially with respect to a blank while the center of the cutting element and blank are rotated relative to each other to provide a cylindrical surface of fixed radius, and thereafter the valleys are formed by relative radial reciprocating movement between the cutting element and blank until the remaining sections of the cylindrical surface are machined to a predetermined length.

Further objects and advantages will become apparent to those skilled in the art to which the invention relates from the following description of the preferred embodiments described with reference to the accompanying drawings forming a part of this specification, in which:

FIGURE 1 is a perspective view of apparatus embodying principles of the present invention;

FIGURE 2 is a cross-sectional side view of the apparatus embodying principles of the present invention;

FIGURE 3 is a side view of a cam member finish machined according to the preferred cam configuration;

FIGURE 4 is a fragmentary side view of a portion of FIGURE 3 better illustrating a refinement in its contour;

FIGURE 5 is a fragmentary schematic view exaggerating the relationship between the desired cam configuration and cutting element to more fully depict the principles of the invention; and

FIGURE 6 is a fragmentary schematic view exaggerating the relationship between a preferred form of gearing which strangely enough closely approximates a desired corrective phase shifting movement in the above apparatus.

There is shown in the drawings apparatus which is specifically designed to machine the cam configuration illustrated in FIGURES 3 and 4 of the drawings. The cam body member C shown in these views is specifically designed for use in sliding vane cam pumps of the type described in the Burt, Sung and Farron Patent No. 2,985,110, issued May 23, 1961. In this type of pump, a cylindrical rotor member (not shown) is mounted within the central opening 10 of the cam, in sliding sealing engagement with the radially innermost projecting parts or lobes 12 of the cam. The rotor carries a plurality of vanes which are biased radially outwardly into engagement with the cam surface 14, to sweep liquid out of the space defined by the valleys, or cam depressions, and the rotor through suitable passages in the rotor member. For a more complete description of the construction and operation of the pump for which the cam member C is designed, reference may be had to the above mentioned application.

The specific pump of which cam member C is a part is intended for use in hydraulic power steering systems where substantially pulse free flow is required at rotor speeds ranging from 100 to 4000 r.p.m. and at pressures in excess of 1000 p.s.i. Numerous problems are involved in designing pumps for these conditions. One of these problems is presented by leakage from a high pressure valley to a low pressure valley through the clearance between the separating lobe and rotor; and another of these problems is presented by the dynamic forces of the vanes which tend to separate them from the cam surface. The specific cam contour used in the cam member C is a sinusoidal one conforming to the equation $R=r_b+e\cos n\theta$. For a more detailed description of this contour and of the problems of designing pulse free pumps, reference may be had to the above referred to application.

In his work with such pumps, applicant has found that a great reduction in leakage between the cam surface and rotor can be accomplished by means of a cylindrical contour in the tip of each lobe without harmfully affecting the pulse free operation of the pump. These cylindrical contours should be confined to the tips of the lobes; and should preferably extend over an arc of from about 2 to about 5 degrees.

The method and apparatus used by applicant to machine the cam contour previously described may best be understood by reference to FIGURE 5 of the drawings, wherein the pertinent angles and distances are shown exaggerated to better illustrate the relationship involved. The desired finished machined contour is generally indicated at 15 and the periphery of a rotatable cutter of predetermined diameter for machining the contour is indicated at 16. There is also shown at 18 a line all points on which are spaced radially inwardly from the line 15 towards the center O of the blank a distance R which corresponds to the radius of the cutter 16. Relatively simple means could be provided for moving the center of the rotatable cutter along line 18; but were this to be done, the cutter would not be tangent to the desired contour as seen by the dot-dash line 20, but would "dig out" too much metal at some spots and not enough at others. In order for the above described cam contour to be able to develop substantially pulse free discharge, the cam contour must be machined to an accuracy approaching a few ten thousandths of an inch. This can only be obtained by correcting for the above-stated inaccuracy involved in the use of a rotatable cutter.

The applicant has theorized that the above errors could be eliminated were means to be provided which, if kept in phase relationship with the angle of rotation of the blank, would move the center of the cutter along a path which is a fixed radial distance from the desired cam contour (i.e. along the line 18); and further has theorized that by suitably changing the phase relationship between the cutter and the blank, the periphery of the cutter could be made tangent to the desired contour at all times. A preferred method of accomplishing these results will now be explained with reference to FIGURE 5 of the drawings. Assume for the time being that a suitable means is used to provide radial movement between the cutter and the blank, and that a further means is provided which, when rotated in direct proportion to said first means, moves the center of the cutter along the line 18. Referring to FIGURE 5, the equation for the desired cam contour 15 will be:

$$r_\phi=r_b+e\cos n\phi$$

where

r_ϕ=radius of any point of the cam defined by angle ϕ

r_b=mean base circle for the cam

e=maximum variation above and below the base circle
n=number of lobes
ϕ=the angle between any particular radius and an arbitrary reference line through a center of a valley.

For a cutter of radius R, the radius of curve 18 at any given point could be $r_c=r_b-R+e\cos n\phi$.

It will be seen that if the cutter is moved in and out on its radius in phase with its position about the cam its center would be at 22 at the angle ϕ shown in FIGURE 5. If the center 22 were moved radially inwardly to the point 24, the cutter would be tangent to the desired contour at the point T. Point 24 is the distance S from the cener O; and if the cutter were moved out of phase by the angle θ, it would have a radius equal to S. Therefore to be tangent, the means moving the cutter radially would have to have moved an angle proportional to β when the cutter had moved ϕ. By means of polar coordinates:

(1) $$\tan\psi=\frac{r_\alpha}{\frac{dr}{d_\alpha}}=-\frac{r_b+e\cos n\alpha}{en\sin n\alpha}$$

(2) $$S^2=r_a{}^2+R^2-2r_a R\cos(90-\Psi)$$

(3) $$S=r_b-R+e\cos n(\phi+\theta)$$

rewriting 3

$$\cos n(\phi+\theta)=\frac{1}{e}[R-r_b+S]$$

and

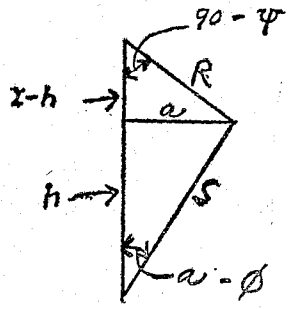
$$\theta=\frac{1}{n}\arccos\frac{1}{e}[R-r_b+S]-\phi$$

also from the law of sines

$$\frac{S}{\sin(90-\Psi)}=\frac{R}{\sin(\alpha-\phi)}$$

(4) $$\phi=\alpha-\arcsin\frac{R\sin(90-\Psi)}{S}$$

Constructing a normal from point 24 to the radian



$$\sin(99-\psi)=\frac{a}{R}$$

$$a=R\sin(90-\psi)$$

$$\cos(90-\psi)=\frac{r_a-b}{R}$$

$$h=r_a-R\cos(90-\psi)$$

(5) $$\tan(\alpha-\theta)=\frac{R\sin(90-\psi)}{r_a-\cos(90-\psi)}$$

(6)

$$\therefore\theta=\frac{1}{n}\arccos\frac{1}{e}[R-r_b+S]-\alpha+\arctan\left(\frac{R\sin(90-\psi)}{r_\alpha-R\cos 90-\psi)}\right)$$

where

$$s=\sqrt{r^2+R^2-2r_\alpha R\cos(90-\psi)}$$

and

$$\psi=\arctan-\left(\frac{r_b+e\cos n\alpha}{en\sin n\alpha}\right)$$

The above equation expresses the manner in which θ must vary with respect to ϕ and shows the relationship between θ and ϕ to be quite complicated.

Applicant further investigated the manner in which a first cylindrical gear journalled about a point spaced a distance a from its center would rotate a similar gear also journalled a distance a from its center. The arrangement investigated is seen in FIGURE 6 where the various angles and distances are appropriately labeled and from which the following equations are developed:

(7) $$D^2=R^2+a^2-2aR\cos(180-P)$$

$$D=\sqrt{R^2+a^2+2aR\cos P}$$

$$R^2=F^2+a^2-2aF\cos(180-x)$$

$$F^2+2aF\cos x+(a^2-R^2)=0$$

$$F=-\frac{2a\cos x\pm\sqrt{(2a\cos x)^2-4(a^2-R^2)}}{2}$$

(8) $$F=-a\cos x\pm\sqrt{R^2-a^2\sin^2 x}$$

$$P=\arcsin\left(\frac{F\sin x}{R}\right)=\arccos\left(\frac{F\cos x+a}{R}\right)$$

$$\phi=\arcsin\left(\frac{F\sin x}{D}\right)$$

$$\phi=\arcsin\frac{(-a\cos x\pm\sqrt{R^2-a^2\sin x})\sin x}{\sqrt{R^2+a^2+2aR\cos P}}$$

$$\phi=\arcsin\frac{(-a\cos x\pm\sqrt{R^2-a^2\sin^2 x})\sin x}{\sqrt{R^2+a^2+2aR\left(\frac{F\cos x+a}{R}\right)}}$$

(9)

$$O=\arcsin\frac{(-a\cos x\pm\sqrt{R^2-a^2\sin^2 x})\sin x}{\sqrt{R^2+3a^2+2a\cos x(-a\cos x\pm\sqrt{R^2-a^2\sin^2 x})}}$$

and $x-\phi$ should approach n times the theoretical θ of Equation 6.

By cut and try methods applicant was able to establish that, when $r_b=1.25$, $R=.375$, $n=6$, $e=.023$, $R-1$ for the gear, and the a value of the theoretically desired contour.

A tabulation of data indicating the accuracy with which the S value provided by the gearing approaches the theoretically required S value for a perfect contour is as follows:

Assuming values of α as indicated,

	S	sin (90−ϕ)	$\frac{R\sin(90-\psi)}{S}$	arc sin $\frac{R\sin(90-\psi)}{S}$			ϕ		
				°	′	″	°	′	″
5	.89570	.0542531	.022714	1	18	4	3	41	56
8	.89213	.0807788	.033955	1	56	45	6	3	15
10	.88888	.0943158	.039790	2	16	50	7	43	10
12	.88499	.1038389	.044000	2	31	19	9	28	41
15	.87823	.1097343	.046856	2	41	8	12	18	52
18	.87086	.1050154	.045221	2	35	31	15	24	29
20	.86599	.0960484	.041781	2	23	39	17	36	21
23	.85941	.0746887	.032590	1	52	4	21	7	56
25	.85593	.0560054	.024537	1	24	21	23	35	39

6φ input angle of gears			x output angle of gears		cos xh=0.23 cos xS−1.25−.375h−a			
°	′	″	°	′				
22	11	36	25	30	.90259	.02076	.02070	.00006
36	19	30	41	25	.74992	.01725	.01713	.00012
46	18	0	52	28	.60922	.01401	.01388	.00013
56	52	6	63	55	.43968	.01011	.00999	.00012
73	53	12	81	48	.14263	.00328	.00328	.00005
92	26	54	100	33	−.18309	−.00421	−.00414	−.00007
105	38	6	113	16	−.39501	−.00909	−.00901	−.00008
126	47	36	132	59	−.68179	−.01568	−.01559	−.00009
141	33	54	146	21	−.83244	−.01915	−.01907	−.00008

It will be seen that the maximum error is less than 2 ten thousandths of an inch and is therefore acceptable.

Apparatus embodying the above principles is shown in FIGURES 1 and 2 of the drawings. The apparatus generally comprises a frame A on which is journalled a turntable B for supporting and rotating an annular blank C to be machined. The blank is machined by a rotatable cutter D carried by a high speed electric motor E, which in turn is mounted on a slide F adapted to be reciprocated so that the cutter moves in a straight line which passes through the center of the blank. The slide F is moved back and forth by means of the eccentric G which in turn is rotated by means of gearing H which provides the proper lead and lag to an in-and-out movement of the slide to maintain the cutter tangent to the desired contour, as discussed above.

The turntable B for supporting and rotating the blank C comprises a bottom plate 30, the under surface of which is accurately machined to revolve on a corresponding surface 32 machined into the top face of a horizontal plate 34 of the frame A. A facing plate 36 recessed in its upper face to receive the bottom end of the cutter D and to provide chip space is suitably fastened to the plate 30; and the blank C is adapted to be clamped thereto by the bolts 38. The turntable assembly B is rotated by means of a shaft 40 suitably journalled in the frame A; and the bottom end of shaft 40 is coupled to the output shaft 42 of a gear reducer 44 having an input shaft 46 adapted to be driven by an electric motor (not shown).

The blank C will usually be rough machined to an internal diameter approaching the desired distance between opposite lobes of the finished cam. The rotatable cutting element D adapted to machine the finished contour is rotatably supported from the electric motor E which in turn is supported from the slide structure F about to be described. The top plate 48 of the frame is machined parallel to the machine surface 32 to provide a suitable surface on which the slide structure F reciprocates. Opposite side edges of the slide F are beveled for sliding engagement with a pair of ways 50 and 52 which in turn are bolted to the top plate 48 in a manner assuring that the cutter D will move radially across the centerline of the turntable B. The electric motor E is supported from the slide F by means of blocks 54 and 56, the adjacent ends of which are suitably recessed to receive opposite sides of the electric motor E; and the electric motor is clamped therebetween by means of the machine bolts 62. The block 54 is in turn adjustably positioned upon the slide F by means of a plurality of bolts 64 which extend through slotted holes 66 in the block 54 and are threaded into the slide plate F. Suitable openings 68 and 70 are provided in the slide plate F and the top plate 48 of the frame, respectively, to receive the electric motor E and permit lateral movement thereof relative to the blank C.

The slide F is adapted to be reciprocated generally according to a desired sinusoidal function by an eccentric G and a scotch yoke structure 72 fixed to the slide plate F. The scotch yoke structure 72 is formed by means of a pair of blocks 74 and 76 adjacent sides of which are suitably recessed to receive opposite sides of a cylindrical rotor 78. The blocks 74 and 76 are confined into tight engagement with opposite sides of the rotor 78 by means of a cross-bar 80 and through bolts 82 and 84 which extend through openings in opposite side spacer members 86 and 88 and are threaded into the end of the slide plate F. The spacer members 86 and 88 are of a length which will provide a tight fit between the rotor 78 and the blocks 74 and 76 to overcome lost motion in the reciprocating structure. The reciprocating cycle of the cutter D may be fed radially outwardly into the blank by means of a hand wheel 90 and rod 92 which is threaded into a support block 94 and the end of which is adapted to abut the block 54. The support block 94 is fixed to slide F by bolts 96; and the end of the rod 92 adjacent the hand wheel 90 is slidably received in an opening 98 in a guide plate 100 suitably fixed to the frame A. The block 54 carrying the motor E has been previously described as being adjustably fixed to the slide plate F by means of slotted holes 66 and bolts 64; and by threading the rod 92 inwardly against the block 54, the block 54 may be moved relative to the slide plate F. A dial indicator 102 is shown mounted on the block 54 with its sensitive element in engagement with the support block 94 such that the depth of cut of the cutter D can be readily determined. As a practical matter, the bolts 64 may be tightened to a point wherein friction between the block 54 and slide plate F is sufficient to hold the cutter into cutting engagement with the blank and yet still permit the block 54 to be moved relative to the slide by means of the threaded rod 92 without further adjustment of the bolts 64.

The cylindrical rotor 78 is mounted eccentrically on the end of a shaft 104 by a distance *e* which in the present instance is equal to 0.023 inch. The shaft 104 is suitably journalled in the frame A and is driven at a rate which is generally six times that at which the blank is rotated to provide a cam having six lobes and six valleys. The shaft 104 is driven from a jackshaft 106 by means of gearing H later to be described and the jackshaft 106 is suitably journalled in the frame A and driven at a rate six times that of the shaft 40 by means of gears 108 and 110 fixed to the shafts 40 and 106 respectively.

The gear means H is adapted to provide the correction by means of which the cutter element D is maintained tangent to the desired cam contour, utilizing the principles previously described with reference to FIGURE 6 of the drawing. The gear means H comprises two cylindrical gears each having a pitch diameter of two inches and each of which is mounted on its respective shaft eccentrically by a distance *a*, which in the present instance is equal to 0.106 inch. The gear 112 which is fixed to the shaft 106 will correspond generally to the left-hand gear depicted in FIGURE 6; and the gear 114 fixed to the shaft 104 will correspond to that shown in the right-hand side of the same figure.

In the preferred method of operating the apparatus above described, a gear blank C finished to a rough internal diameter will be bolted to the turntable B. The cutter D will be positioned within the opening of the blank C, and the gear 112 will be removed from the shaft 104 so that the slide F will not be reciprocated relative to the blank. The hand wheel 90 will be turned to gradually advance the rotating cutter D radially into the blank C until its internal diameter corresponds to the desired distance between the cylindrical surfaces 116 in opposite lobes of the finished cam. Once this diameter has been accurately machined the gear 112 is inserted upon the shaft 104 and the eccentric means G suitably rotated to provide reciprocatory movement of slide structure F. Prior to the time that the slide structure F is reciprocated relative to the blank, the motor E will be moved radially inwardly a sufficient distance such that the cutter D will not engage the surfaces of the blank about to be machined when the reciprocation of the slide structure is started. Thereafter the rod 92 is threaded inwardly until the reciprocatory cycle is moved outwardly to a point where the cutter D begins to engage the blank during the radially outermost portion of its cycle. Engagement of the cutter D during its outermost extremity

of radial movement begins to form the valleys in the blank C; and by gradually advancing the rod 92 into the support member 94, these valleys will be deepened until all that remains of the original cylindrical internal surface are the sections which are to be left in the tips of each of the lobes. These cylindrical surfaces 116 will preferably be from 2 to 5 degrees in length. It will be seen that the chordal length of the cylindrical surfaces 116 will be gradually reduced as the machining of the cam progresses. The cylindrical surfaces 116 provide a mark which can readily be seen by the operator; and when this mark has decreased to approximately 50 or 60 thousandths of an inch (which can be judged by eye, by a skilled machinist) the machining of the cam is complete. By this simple expedient the sinusoidal surfaces can be accurately machined to the desired depth. The apparatus shown in the drawings can be used to machine external cams as well as internal cams; and by suitably alternating the eccentric G and gearing H the same principles can be used to form cams having a configuration other than the sinusoidal one of the cam shown in FIGURE 3.

While the invention has been described in considerable detail, I do not wish to be limited to the particular methods and constructions shown and described, and it is my intention to cover hereby all novel adaptations, modifications and arrangements thereof which come within the practice of those skilled in the art to which the invention relates.

I claim:

1. The method of machining the fluid pressure chamber forming cam member of a vane type positive displacement fluid handling device, comprising: moving a rotating cutting element radially with respect to a rotating blank until a cylindrical surface of said predetermined diameter is formed; thereafter reciprocating said rotating cutting element radially with respect to said rotating blank according to a predetermined cycle; and gradually advancing said reciprocating cycle of said cutting element radially with respect to said cylindrical surface to gradually remove more and more metal until the remaining cylindrical surfaces are of a predetermined length.

2. The method of machining the fluid pressure chamber forming cam member of a vane type positive displacement fluid handling device in a machine having means for supporting a blank, means for supporting a rotatable cutter, means for producing relative rotation between the blank and cutter, and means for moving the blank and cutter radially relative to each other, said method comprising: mounting the blank in the machine; providing relative rotation between the blank and the center of the cutter; gradually moving the cutter and blank radially relative to each other until a cylindrical surface of predetermined diameter is generated; moving the cutter and blank radially relative to each other to a non-cutting position; providing a relative radially reciprocating movement between the blank and cutter in predetermined phase relationship to relative rotational movement between the blank and cutter; and gradually advancing the radially reciprocating movement between the cutter and blank into the cylindrical surface of the blank until the remaining portions of the cylindrical surface are of a predetermined length.

3. The method of machining the fluid pressure chamber forming cam member of a vane type positive displacement fluid handling device in a machine having means for supporting a blank, means for supporting and rotating a rotatable cutter, means for moving the blank radially with respect to the cutter, and means for moving the blank and cutter radially relative to each other, said method comprising: mounting the blank in the machine; gradually moving the cutter and blank radially into the rotating blank until a cylindrical surface of predetermined diameter is generated; moving the cutter radially out of cutting engagement with respect to the blank; providing a cyclic radially reciprocating movement to the cutter in predetermined phase relationship to the rotation of the blank; and gradually advancing the cycle of the cutter into the cylindrical surface of the blank until the remaining portions of the cylindrical surface are of a predetermined length.

References Cited by the Examiner

UNITED STATES PATENTS

1,833,003	12/31	Hill	90—3
2,917,693	12/59	Cail.	

WILLIAM W. DYER, JR., *Primary Examiner.*

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,177,774 April 13, 1965

Farlow B. Burt

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 3, line 57, the equation should appear as shown below instead of as in the patent:

$$\cos\ (90-\psi) = \frac{r_\alpha - h}{R}$$

line 61, the equation should appear as shown below instead of as in the patent:

$$\tan\ (\alpha-\phi) = \frac{R \sin\ (90-\psi)}{r_\alpha - R \cos\ (90-\psi)}$$

Signed and sealed this 12th day of October 1965.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

EDWARD J. BRENNER
Commissioner of Patents