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N/C Non-circular Gear Shaper by Hobbing Method*

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This gear generating machine is designed to cut the gear by the shaping method in which the cutter head having a hob cutter moves vertically. In this case, the hob makes an intermittent index rotation at every half stroke to move the rack in the direction of X axis and to lift the cutting edge in the returning stroke. Synchronously with this, the table is tape-controlled to make the relative angular displacement as well as the movement in the direction of Y axis and set up an automatic cycle. In this way, this machine generates non-circular gears of various dimensions.

Consequently, the machine is not only made simple in construction but also makes it possible to meet the quantitative demand as well as the qualitative demand for improved accuracy and uniformity of the generated gears. The machine can be used to produce many kinds of non-circular gears more easily than a conventional machine.

Introduction

Oval Engineering Co., Ltd. has developed a numerically controlled non-circular gear shaper for generating the oval gear rotor.

The rotor is one of the company's principal products and is used as the most important element of the oval gear positive displacement flow meter. The oval gear is the type of gear whose rolling curve is an elliptic two-lobed curve.

In the conventional method, the teeth of the oval gear have been semi-automatically generated on a modified hobbing machine or a gear shaper. In addition to the ordinary reciprocating motion of the cutter, a cam is employed to regulate the rotational motion as well as the linear (in the X and Y axes direction) motion of the table. A machine of this type, however, requires more time and higher skill in operation than in the spur gear cutting. Another defect of this type machine is its low productivity.

Therefore, the company decided to design a numerically controlled non-circular gear generator for the purpose of correcting these defects.

It has been said that the numerical control method is technically most suitable for this kind of machine.

Before 1958, however, the numerical control technique was not yet fully developed and there were many difficult problems in the design, the cost and the operating methods.

On the cutting motion mechanisms, one of the authors investigated a new adaptable method for numerical control (1958). In 1959, a reliable pulse motor was developed and all dimensions of a numerically controlled machine were determined and the machine was completed in 1962.

Specifications of this machine are shown below

Maximum diameter of work	150 mm
Maximum width of work	260 mm
Maximum module	1.5
Strokes per minute	15~120
Cutting speed	3.75~30 m/min
Maximum chip area	4 mm ² (cast iron)
Response of electro-hydraulic pulse motor	500 p/sec
Output torque of pulse motor	2 kg·m
Hydraulic pressure	70 kg/cm ²
Total input power	22 HP

Principle of generating gears (summary of machine fundamental)

Any generating method of circular gears has a corresponding method for generating non-circular gears. The only difference between the generating method of circular gears and that of non-circular gears lies in the varying rotating speed of the work.

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There may be a special cutting tool for a non-circular gear, but in this machine is used the conventional hob cutter and a special cutting motion is given to the cutter.

Generating motion As this machine uses a conventional hob cutter, the generating motion is identical with the engagement motion of a rack and a non-circular gear so that we first need to consider the general relations about rolling curves along their pitch lines.

Referring to Fig.1 which represents the two curved surfaces in contact at the point P, the rack's curve R is shown by the cartesian coordinates $x = X(t)$, $y = Y(t)$. The gear curve R_1 is shown by the polar tangential coordinate $P = P(\varphi)$.

$$\left. \begin{aligned} a &= y + P \cos \alpha - \dot{P} \sin \alpha \\ x' &= x - P \sin \alpha - \dot{P} \cos \alpha \\ \theta &= \varphi - \alpha \end{aligned} \right\} \dots\dots\dots (1)$$

If these curves roll without a sliding, a line element at P on one curve must be as long as the line element at P on the other curve. The line elements may be written as

$$ds = \sqrt{\dot{X}^2 + \dot{Y}^2} dt, \quad ds_1 = \rho d\varphi = (P + \ddot{P}) d\varphi$$

Fig. 1 The relationship between the pitch curve and the rolling motion (When one is rotating and the other is linearly displacing)

The rolling condition is

$$\int P d\varphi + \dot{P} = \int \sqrt{\dot{X}^2 + \dot{Y}^2} dt + s_0$$

where

$$\begin{aligned} \dot{X} &= dx/dt, \quad \dot{Y} = dy/dt, \quad \dot{P} = dP/d\varphi, \\ \ddot{P} &= d^2P/d\varphi^2 \end{aligned}$$

Since the relation between the two parameters t and φ is known from the above equations, each of the dimensions for gear cutting motion, a , and θ can be evaluated by Eq. (1).

Shown as an example of operational calculation, differential increments are

$$\begin{aligned} da &= (P \sin \alpha + \dot{P} \cos \alpha) d\theta \\ dx' &= (P \cos \alpha - \dot{P} \sin \alpha) d\theta \end{aligned}$$

As an actual non-circular gear has a nearly standard involute profile, the cutting pitch curve of rack becomes a straight line, (Fig. 2), that is, in Eq. (1) $\alpha = 0$ ($y = y_0 = \text{const}$).

Hence, the relation and the condition of the cutting motion are as follows :

$$\left. \begin{aligned} a &= y_0 + P \\ x' &= x - \dot{P} \\ \theta &= \varphi \end{aligned} \right\}$$

The rolling condition is

$$\int P d\varphi + \dot{P} = x + s_0$$

Therefore, each of the dimensions for gear cutting motion can be evaluated by the following Eq. (1)'

$$\left. \begin{aligned} a &= P + y_0 \\ x' &= \int P d\varphi - s_0 \\ \theta &= \varphi \end{aligned} \right\} \dots\dots\dots (1)'$$

Differential increments are

$$da = \dot{P} d\theta, \quad dx' = P d\theta$$

Construction of gear generator The relations

Fig. 2 The relationship of rolling motion between the standard rack and the pinion

in the gear cutting motion are known by Eq. (1)' but for the purpose of simplifying the machine mechanisms controlled by the command on the tape, the rack displacement is made intermittent. The center distance a , and the argument θ would be varied intermittently. This simplifies the design of the machine as shown in Fig. 3.

The hob cutter does not cut rotatingly like a general hobbing machine but cut with strokes up and down like a rack-type gear shaping machine. Hob cutter is turned by $360 \times 1/2N$ degrees (where N is the number of hob grooves) up and down end points. During the down stroke a cutting face shapes the work like a rack cutter, and when it reaches the lower end the cutter is indexed by a half of the grooved angle.

There is a clearance between the work and the cutting edge in the upper return stroke. At the upper end, the cutter is indexed by a half of the grooved angle displacing the rack profile by one pitch divided by the number of grooves. Thus the rack displaces intermittently by a constant amount in each stroke. During the return stroke of the cutter head, the master worm and the cutting depth (screw feed) should displace by an appointed amount.

Actually, these displacements of the master worm and the feed screw are controlled by an electrohydraulic pulse motor, which is driven by command pulses from the numerical controller.

Control system

Table positioning control The number which indicates the table position must have five digits, because the table must be positioned with a minimum

Fig. 3 Sketch of N/C gear generator

Fig. 4 Block diagram of electro-hydraulic pulse motor

increment of several microns in the full stroke of several hundred millimeters. Digital method will be effective for this kind of system and the electrohydraulic pulse motor, recently developed, will control the table positioning accurately in the open loop system. The angular position and the rotating speed of the electrohydraulic pulse motor are controlled quickly and accurately by its input electric pulse train.

The block diagram and the rating of the motor are shown in Fig. 4 and Fig. 5, respectively. The output shaft of the electrohydraulic pulse motor rotates exactly three degrees per one electric pulse. The table can easily be positioned by giving the motor the appropriate number of electric pulses.

So, it is necessary to generate an adequate number of electric pulses to position the table.

Command pulse for positioning table The table motion is the resultant of the angular displacement $\Delta\theta$ and the straight displacement Δa from the table center toward the hob cutter. Two pulse trains corresponding to $\Delta\theta$ and Δa respectively are given to the electrohydraulic pulse motors.

Sets of two numbers Δa and $\Delta\theta$ are previously computed and punched on the 6 channel paper tape as $\{\Delta a_1, \Delta\theta_1, \Delta a_2, \Delta\theta_2, \dots, \Delta a_n, \Delta\theta_n\}$. This tape is the input to the numerical controller. When a cycle of the cutting motion of the hob cutter finishes, the photo-tape-reader reads the information of the tape ($\Delta a_i, \Delta\theta_i$) at a rate of 200 characters per second quickly enough before the next cycle of the cutting motion starts. These data are stored into the a and θ register.

Command pulse trains are generated from the

Type.....model 1
 Angular deviation per pulse.....3 deg
 Supply oil pressure (max.).....1 000 psi
 Torque output.....170 lb-in (at 500 pps, 1 000 psi)
 Power output.....1HP (at 1 000 pps, 1 000 psi)
 Allowable load inertia (max.)..... 1.3×10^{-2} lb-in-s²
 Displacement per revolution.....1.65 in³
 Weight.....44 lbs

Fig. 5 Electro-hydraulic pulse motor

well-known pulse distributor, widely applied to the numerical control of milling machines. Fig. 6 shows the principle of the binary pulse distributor. In our system, the decimal pulse distributor is used. The table moves 5 microns per one pulse and turns 2.5 minutes per one pulse.

The pulse distributor can generate up to 99 pulses at one time. The counter and the registers have the capacity of two decimal digits, and an output gate in each digit has five input terminals which correspond to 5, 1, 1, 1, and 1 pulse per 10 pulses.

The clock pulse train has a frequency of 500 pps. The time required for the table positioning is

Fig. 6 Principle of binary pulse distributor

Fig. 7 Internal block diagram of the controls

the same as that for the counter to become of full count, that is, $1/500 \times 100 = 0.2$ second. When the pulse number is under 50, it is so arranged that the table positioning may finish in 0.1 second. Fig. 7 shows the block diagram of the interior of the controls.

Synchronization with the machine Table positioning is made when the hob cutter is not cutting the work piece, therefore it must be synchronous with the machine movement.

The hob cutter goes up and down. Only while it is going down, it cuts the work piece. At the lower end point, the table positioning is made. This up and down motion is mechanically controlled by the ram. A slit disc is attached to the ram shaft, and the rotating angle of the ram is photoelectrically detected for the synchronization with the machine movement.

The sequence of the machine movement and the control is about as follows:

i) At the lower end point, the hob cutter turns by a half of the grooved angle (half of the consecutive two blades) so as not to cut the work piece while it is going up. The table clamp is released.

ii) Table positioning begins on condition that the last setting of the hob cutter has been really done and that the hob cutter is now at the lower end point. After a completion of the table positioning, the controls read in new data from the input tape in preparation for the next table positioning. The servo valve clamps the table.

iii) After a completion of the table positioning, the hob cutter begins to go up. While it is going up, the controls excite the magnet for setting the hob cutter. If it is expected that there will not be enough time for the hob cutter to be set before it arrives at the upper end point, the controls do not excite the magnet.

iv) At the upper end point, the hob cutter turns by a half of the grooved angle so as to be able to cut the work piece while it is going down. (This is called the setting of the hob cutter).

v) The hob cutter goes down and cuts the work piece.

Then the sequence goes back to the beginning to be repeated.

At the lower end point, the controls examine whether the hob cutter setting has really been done. If it has not, the next table positioning will not be done. The reason is this: As the hob cutter to the table changes and the table position is defined by the input tape relatively to the position of

Fig. 8 Sequence diagram

the teeth, the table positioning and the hob cutter setting must necessarily be done one after another. If one has not been done, the other must not be done so that one may never skip the other.

On the operation panel of the controls there are lamps which show the state and the motion of the machine for ease of operation and maintenance.

The dials of the manual operation panel are used to move the table manually. The dial turns the slit disc which generates photoelectrically electric pulses to move the electrohydraulic pulse motor.

Fig. 8 shows the sequence diagram of the controls and the machine.

Cutting data

In order to check the accuracy of the completed N/C non-circular gear generator, an eccentric gear cutting of the circular gear was tried.

The eccentric gear cutting means a circular gear cutting of an eccentric center. Reasons for choosing this type of cutting are similarity to the non-circular gear cutting procedure and the easiness of precision measuring of the produced gear because in measuring the non-circular gear the circular gear measuring method may be applied.

So referring to Eq. (1)' and Fig. 9, the rolling

Fig. 9 Rolling motion of an eccentric circle

Fig. 10 Sketch of eccentric gear

Fig. 11 Pin check of an eccentric cut gear

Fig. 12

curve is given by an eccentric circle and each element of gear cutting motion is as follows:

$P = \rho + e \cos \varphi$ (eccentric circle given by polar tangential coordinate)

$$a = \rho + e \cos \varphi, \quad x' = \rho \varphi + e \sin \varphi$$

$$\theta = \varphi, \quad da = -e \sin \varphi d\theta$$

$$dx' = (\rho + e \cos \varphi) d\theta$$

an example with

Table 1 Comparison among the N/C generator and other machines

Machine	No. of strokes per minute or rpm						Speed of cutting m/min						Total No. of strokes to complete cutting a gear					
	2A	2B	4A	4B	6A	6B	2A	2B	4A	4B	6A	6B	2A	2B	4A	4B	6A	6B
N/C gear generator	Stroke 56	56	56	47	56	47	20.7	20.7	29.2	24.5	29.2	24.5	600	600	810	810	810	810
Hobbing machine (F)	rpm 196	150	196	150	196	150	61.7	41.7	61.7	41.7	61.7	41.7	75	75	110	110	110	110
Hobbing machine (K)	rpm 166	166	—	—	—	—	52.2	52.2	—	—	—	—	100	100	—	—	—	—

Time required for cutting a gear

Machine	Gear type	2A	2B	4A	4B	6A	6B
N/C gear generator		1.0 (5.36)	1.0 (5.36)	1.0 (7.23)	1.0 (8.62)	1.0 (14.46)	1.0 (17.23)
Hobbing machine (F)		3.0 (15.8)	3.4 (18.0)	4.8 (35.0)	4.9 (42.0)	4.31 (62.0)	4.1 (71.0)
Hobbing machine (K)		4.5 (24.0)	4.5 (24.0)	—	—	—	—

Note: 1. Cutting time is taken as unity with N/C machine.

2. The symbols A and B are A1BC2 and FC25 respectively.

3. In the terms 2A 6B, the numbers 2, 4 and 6 represent coefficients relating to the size of the oval gear.

Tooth profile error

Tooth profile error

Fig. 13 Curve error

Fig. 14

$m=1$, $PA=20^\circ$, No. of teeth=60, Eccentricity $e=15$ mm is shown in the following figures.

Fig. 10 shows the sketch of an eccentric gear.

From Fig. 11 to Fig. 13 are shown the runout curves of teeth groove, pitch error and curve error.

Characteristics of the oval gear positive displacement flow meter The characteristic curve of the flow meter which contains the oval gears cut by the new N/C hobbing machine is compared with the characteristic curve of an ordinary meter in Fig. 14.

It has been observed that:

i) The curve has been made smoother by the new machine, suggesting that the present limits of the tolerable error (ordinarily 0.5%) may be narrowed.

ii) The characteristic curves obtained with many meters have become consistent, showing that this machine can produce oval gears with little individual errors.

Oval gear can be produced by this machine with not only a high accuracy but also a good productivity. Table 1 shows an example of how time is saved with this machine in cutting gears.

Only 1/3~1/5 of the ordinary cutting time is necessary.