Worm Gear with Backlash-Adjustable Toothing

Offprint from *Antriebstechnik* 30 (1991) No. 4

Low backlash is an important property of gear units in many of today's applications. Worm gear with Duplex toothing fulfills this requirement in a simple manner. They allow a directed, sensitive adjustment and re-adjustment of the necessary minimum flank clearance every time, without tampering with the exact geometric contact behaviors. The following article describes the principle and effectiveness of the DUPLEX toothing, explains its advantages compared to other gear adjustment options, and goes into the detailed ascertainment of the screw width and the method of adjustment.

1. Introduction

In the last 20 to 30 years, the meaning and importance of worm gear has strongly increased in several technical areas. On the one hand, this is attributed to the continuous progression of transferable performance and efficiency through intensive research and use of the most modern calculation methods, and on the other hand, to the consequent utilization of the worm gear advantages against other gear mechanisms.

Worm gear runs at a low and muffled noise level, allows for large conversions in one level and builds smaller than other gear mechanisms used for the same operation and conversion. They are found in a wide range of applications in the area of low backlash and backlash-adjustable drives. It is here that the DUPLEX toothing (Figure 1) especially proves its worth.

2. Utilization and Fields of Application

Low backlash worm gear is required anywhere where

- exact and consistent transmission of rotary motion or
- exact adherence to a certain, predetermined position is depended upon. In particular, they should prevent changes or fluctuations in torque from influencing the steadiness of the kinetics during operation.

Examples for the application of low backlash worm gear are:

- printing units,
- actuating drives for beam antennae and solar panels,
- industrial robots,
- measuring devices,
- machine tools,

in which the advantages of worm gear such as

- high conversion realization in one level,
- 90 degree axial angle,
- muffled, low-noise and low vibration operation,
- high power density with good efficiencies,
- simple implementation of self-locking capability

fully establish its worth.

Fig. 1 MUTAX-DUPLEX-Worm Gear Set

3. Free from Backlash or Low Backlash?

Implementing worm gear sets with complete freedom from backlash is neither reasonable nor practical. A minimized flank clearance is necessary for several reasons:

It is conducive to the equalization of unavoidable toothing tolerances and allows for the accumulation of a lubricating film between the teeth flanks meshed with one another. A good elastohydrodynamic lubricating film accumulation increases the load-carrying capacity, alleviates the thermal stress, improves the efficiency and reduces the abrasion caused under stressed conditions.

Furthermore, clamping must be avoided, which could result from differing thermal expansions of the worm gear material (generally steel) and wheel material (generally bronze) and from bending of the worm shaft under outer weights.

In order to achieve an optimal low backlash, MUTAX-DUPLEX toothing is produced by default in heightened quality. A further improvement of the running precision can be accomplished with an additional systematic intake procedure.

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4. Principle and Effectiveness of DUPLEX-Toothing

In contrast to normal toothing (also known as SIMPLEX-worm gear), tooth flanks of DUPLEX worm gear are manufactured with differing modules such as diameter quotient. This results in different angles of gradient for the two tooth flanks, such that the tooth thicknesses and tooth gaps change continually over the worm toothing widths (Figure 1).

At the worm gear wheel, the varying modules bring forth different addendum modification coefficients and pitch circle diameters, and thus flank forms for the front and rear flanks that diverge from one another. The tooth thicknesses and gaps remain constant at the contact point with the wheel.

The backlash adjustment is effected through axial displacement of the worm gear, such that the area of the worm gear toothing comes into mesh with the tooth thickness that is in line with the tooth flank backlash. The tooth flank clearance can be adjusted on every arbitrary value and be re-adjusted sensitively and continuously every time, without changing the mesh ratio of the toothing.

5. Other Potentials for Backlash Adjustment

Other than the DUPLEX methods, fundamentally there are also the following potentials for positioning and re-adjusting the tooth flank clearance of worm gear:

- Changes of the distances between axles, in which eccentric bushing (where the worm shaft and/or the worm wheel is supported) is twisted in the casing.
- Axial displacement of a conically arranged worm gear (Figure 2a).
- Separation of the worm gear into two halves (Figure 2b) that are relatively staggered against one another or
- Separation of the wheel into two plates (Figure 2c) that are relatively skewed to one another.
- These methods, however, possess considerable disadvantages:
- Clearance adjustment and re-adjustment distort the exact geometric meshing
- They misalign the tooth bearing and change its form and size. In doing so, they impede the load bearing capacity and degrades the efficiency.
- Each adjustment results in a new intake abrasion.
- The danger of the incorrect adjustment and destruction of the worm gear is substantial.

DUPLEX toothing is not familiar with such problems. This allows for an exact geometrically toothed and furthermore delicate clearance adjustment. Thus neither the once developed tooth bearing nor the bearing strength is influenced. In addition, as involute-toothing, the MUTAX-DUPLEX toothing is relatively inured to changes in the distance between the axles, for example, as a result of worm gear bending.

6. Toothing Geometry

To differentiate the two flanks, following the index, they are identified with G for the flank with the larger module, and K for the flank with the smaller module (Figure 3). N stands for an imaginary flank N whose geometry results from the averaged values for the G and K flanks.

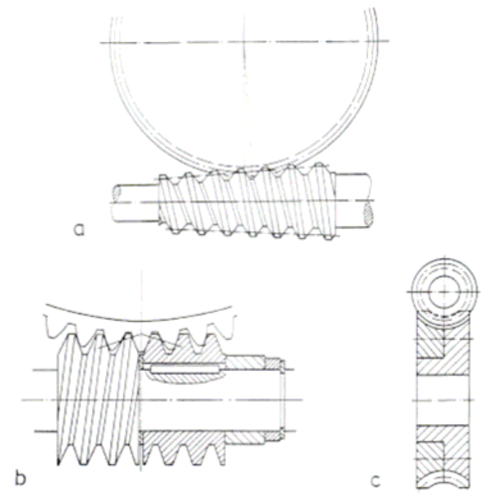

Fig. 2. Possibilities of the backslash adjustment [1]
a: conical screw; b: splittet screw; c: splitted wheel

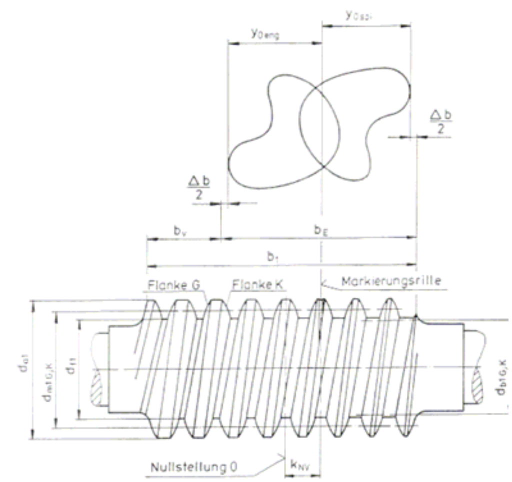

Fig. 3. Contact geometry of a MUTAX DUPLEX worm gear
Description see text

The toothing geometry with the index j for G, K or N is completely described by the following variables:

Number of Gears	z_1
Diameter Quotient	q_j
Module	m_j
Number of Cogs	z_2
Distance between Axles	a
Generation Angle	α_0

With this, all necessary geometric parameters are determined according to [1] or [2]. Tables 1 and 2 summarize the disquisition of required geometric equations.

The diameters of the addendum circle and root circle to be used act in accordance with the values for the so-called N flank, viz.

$$d_{a1,2} = d_{a1,2N} \tag{1}$$

$$d_{f1,2} = d_{f1,2N} \tag{2}$$

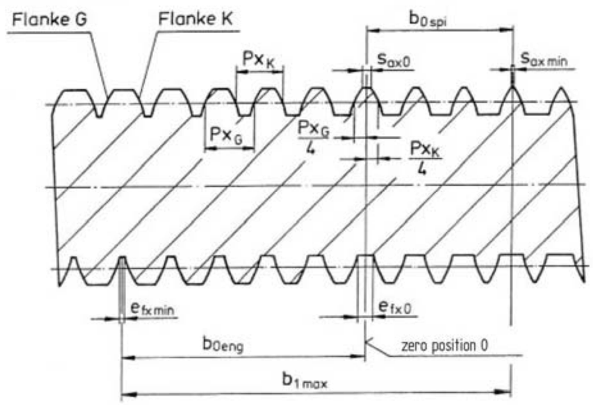

Fig. 4 Maximum screw width
Description see text

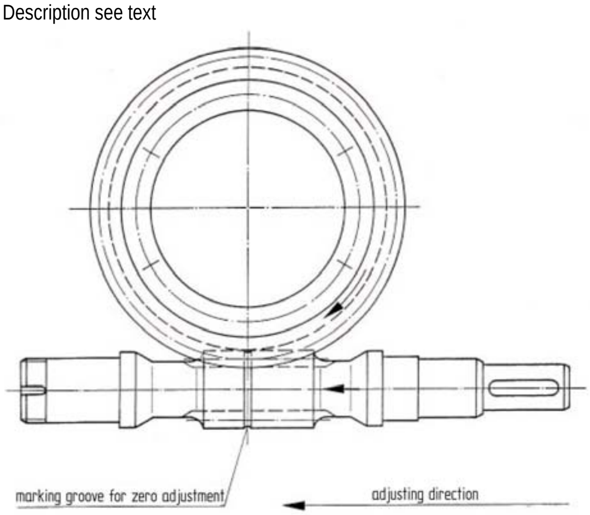

Fig. 5 Marking of the installation conditions

The usable root diameter $d_{Nf1}$of the active flank of the worm gear must be greater than the largest diameter of the base circle in order to ensure that the entire involute profile of the active flanks shows.

7. Limits of the Worm Toothing Width and the Method of Adjustment

The minimum width of the DUPLEX worm gear b_1 is made up of the contact width b_E and the adjustment width b_V

$$b_1 = b_E + b_V \qquad (3)$$

The contact width b_E includes the entire dimensions of the overlaying contact field of the two flanks in the axial direction y_{Oeng} and y_{Ospi} (Figure 3), which is verified from an analysis of the contact behaviors with the help of a calculation program. With this, it is applied according to Figure 3:

$$b_E = y_{Oeng} + y_{Ospi} + \Delta b \qquad (4)$$

The two-sided width allowance Δb/2 ensures that deviations from the theoretical contact resulting from deformations or shape deviations do not lead to contact disturbances.

The adjustment width b_V can be used for backlash compensation.

The overall width b_1 of the worm gear toothing is limited by the fact that the teeth on one side may not become too pointed, and the tooth gaps on the other side may not become too narrow (Figure 4).

Starting from the zero position 0 on the worm gear, where the tooth thickness – measured at the middle circle – is equal to the tooth gaps, the distance to the "pointed" tooth is:

s_{axmin} stands for the minimum tooth point thickness and s_{axo} for the tooth point thickness in the zero position:

$$b_{Ospi} = \frac{(s_{axo} - s_{axmin})(p_{xG} + p_{xK})}{2(p_{xG} + p_{xK})} \qquad (5)$$

$$e_{fxo} = \frac{(p_{xG} + p_{xK})}{4} - (\Delta_{mfG} + \Delta_{mfK}) \qquad (6)$$

with the geometric coefficient for involute profiles

$$\Delta_{mnj} = \frac{1}{2\tan\beta_{bj}}((d_{aj}^2 - d_{bj}^2)^{1/2} - (d_{mj}^2 - d_{bj}^2)^{1/2} - d_{bj}(\arc\cos(\frac{d_{bj}}{d_{aj}})\ \arc\cos(\frac{d_{bj}}{d_{mj}})) \qquad (7)$$

In order to avoid damaging the mating flank during the production of the worm gear, the narrowest tooth gap including the grinding stock, must be larger than the width s_{aw} of the tool at its external diameter.

The distance between the zero position and "narrowest" gap rise to

$$b_{oeng} = \frac{(e_{fx0} - e_{fxmin})(p_{xG} + p_{xK})}{2(p_{xG} - p_{xK})} \qquad (8)$$

Herein applies for the minimum tooth gap:

$$e_{fxmin} = \frac{s_{aW}}{\cos\gamma_{fN}} \qquad (9)$$

and for the tooth gap at the zero position

$$e_{fxo} = \frac{(p_{xG} + p_{xK})}{4} - (\Delta_{mfG} + \Delta_{mfK}) \qquad (10)$$

with the geometric coefficient for involute profiles

$$\Delta_{mnj} = \frac{1}{2\tan\beta_{bj}}((d_{aj}^2 - d_{bj}^2)^{1/2} - (d_{mj}^2 - d_{bj}^2)^{1/2} - d_{bj}(\arc\cos(\frac{d_{bj}}{d_{aj}})\ \arc\cos(\frac{d_{bj}}{d_{mj}})) \qquad (11)$$

The sum of both distances gives the maximum toothing width of the worm gear

$$b_{1max} = b_{Ospi} + b_{Oeng} \qquad (12)$$

In principle, the worm wheel cutter presents an image of the worm gear, by which its width b_{EW} in analogy to b_E must be adapted to the diameter of the wheel to be assembled and thus to the entire contact field that arises.

In the particular case the cutter is shifted relative to the wheel, that the end of the tool with the "pointed" tooth ends with the contact field. With the instrument length l_{WOspi} between the zero position and the of the cutter with "pointed" tooth, arises the displacement from zero position

$$k_{NV} = l_{WOspi} - y_{Ospi} \qquad (13)$$

The displacement from zero position implies, that in order to enable a larger abrasion, on one hand, the permitted adjusting range can be increased, while on the other hand, the cogs can be processed thicker.

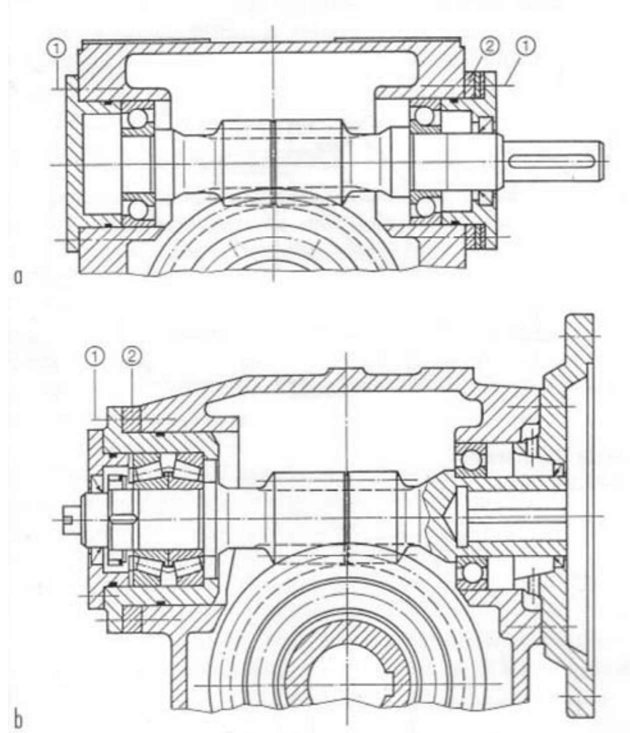

Fig. 6 Worm gear shaft mountings which allow an axial adjustment of the screw
a: Engaged mounting:
1. Remove cover screws 1 at both sides to release cover.
2. Remove the nos. of splitted shims 2 according the required adjustment at the one side and install the at the opposite one
3. Re-tighten the cover screws
b: Fixed-/loose bearing combination:
1. Remove screws 1 at the bearing bushing
2. Remove splitted washer 2 and re-grind it according the required adjustment
3. Re-assemble the washer and tighten the bushing ring

The worm gear shaft must also be staggered for the same amount, such that the gear remains theoretically free of backlash.

The maximum adjusting range results from the aforementioned interrelationships to:

$$b_{Vmax} = b_{1max} - b_E + k_{NV} \quad (14)$$

The required displacement path *k* for the compensation of a tooth flank clearance Δs_2 is calculated with the equation

$$k = \Delta k \cdot \Delta s_2 \quad (15)$$

with the backlash compensation constant according to the relationship

$$\Delta k = \frac{(m_G + m_K)}{2(m_G - m_K)} \quad (16)$$

With this, a maximum tooth flank clearance can be compensated up to

$$\Delta s_{2max} = \frac{b_{vmax}}{\Delta k} \quad (17)$$

It is all the larger, the smaller we choose Δk or the larger we choose the module difference. Here the addendum modification x_2 at the wheel sets the limit.

8. Production

MUTAX-DUPLEX Worm Gear is produced from high alloy case-hardened steel, carbonized and ground. Thus the involute profile, in contrast to the concave flank profile, is not influenced by changes of the grinding wheel diameter. The wheels are milled from premium Ni-bronze with special cutters by gear hobbing.

Worm gears and wheels from MUTAX-DUPLEX toothing are arbitrarily interchangeable, i.e., worm gears and wheels do not need to be produced record-by-record. With this, it is also possible to replace a wheel with a new one without having to replace the worm gear.

Middle Circle Diameter	$d_{nij} = q_j \cdot m_j$
Base Circle Diameter	$d_{b1j} = d_{m1j}$ (tan γ_{mj} / tan γ_{bj})
Addendum Circle Diameter	$d_{a1j} = d_{m1j} + 2m_j$
Root Circle Diameter	$d_{f1j} = d_{m1j} - 2{,}4m$
Axial Pitch	$p_{Xj} = \pi \cdot m_j$
Lead Angle at the Middle Circle	$\gamma_{mj} = \arctan z_1/q_j$
Lead Angle at the Base Circle	$\gamma_{bj} = \arccos(\cos \gamma_{mj} \cdot \alpha_0)$
Lead Angle at the Addendum Circle	$\gamma_{aj} = \arctan(d_{m1j}/d_{a1j} \cdot \tan \gamma_{mj})$
Lead Angle at the Root Circle	$\gamma_{fj} = \arctan(d_{m1j}/d_{f1j} \cdot \tan \gamma_{mj})$
Helix Angle at the Base Circle	$\beta_{bj} = \pi/2 - \gamma_{bj})$

Table 1: Determination Equations for the Worm Gear Geometry
Index j stands for G, K or N

Middle Circle Diameter	$d_{m2j} = 2 \cdot a - d_{m1j}$
Pitch Circle Diameter	$d_{2j} = z_2 \cdot m_j$
Base Circle Diameter	$d_{a2j} = d_{m2j} + 2 \cdot m_j(1 + x_{2j})$
Outer Diameter	$d_{e2j} = d_{a2j} + m_j$
Root Circle Diameter	$d_{f2j} = d_{m2j} - 2{,}4\ m_j$
Addendum Modification Coefficient	$x_{2j} = a/m_j - (q_j + z_2)/2$

Table 2: Determination Equations for the Worm Wheel Geometry
Index j stands for G, K or N

9. Assembly Conditions and Examples

The relative positioning of wheel and gear of a MUTAX-DUPLEX toothing is given due to the unequal flank geometries. They are identified by arrows (Figure 5). During the assembly, the arrow points must point in the same direction. The arrow on the worm gear simultaneously indicates the re-adjustment direction for backlash reduction. A groove at the perimeter conduces to the zero setting. By positioning the worm gear with the groove in the tangent point of the middle circle, the newly-operating worm gear toothing is theoretically free from backlash.

In order to be able to adjust and re-adjust the tooth flank clearance, the casing construction and the type of bearing must allow an axial adjustment of the worm gear. Figure 6 shows two examples and describes the procedure for the clearance re-adjustment.