THERMAL CALCULUS OF THE WORM GEARBOXES IN THE TRANSIENT OPERATING CONDITIONS

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Abstract. The present paper proposes a simple yet efficient method for evaluating the thermal behaviour of worm gearboxes in transient operating conditions. The main characteristic of this proposed method is the estimation of the sump temperature in time, since the limitation of this temperature is the main criterion for gearbox thermal rating. An application and its discussion are given in the final part of the paper.

Keywords. Worm gearbox, thermal calculus, and transient operating conditions.

1. Introduction

In a few practical applications gearbox operation is intermittent and has long pauses between the working periods. This regime permits the sufficient cooling of a gearbox with a small size. Otherwise, this size has to be increased to offer a sufficient thermal transfer surface of the housing to ensure a limited operating temperature. The main papers for worm thermal rating are DIN 3996 [2], AGMA 6034 [1] and Niemann-Winter book [4]. These papers approach the thermal aspects in different ways. But the thermal calculus for transient operating conditions is not presented in full. Niemann-Winter alone [4] develops an approximate method for this special thermal calculus.

Taking into account these considerations, the present paper proposes a simple yet efficient method for evaluating the thermal behaviour of worm gearboxes in transient operating conditions. The main characteristic of this proposed method is the estimation of the sump temperature in time, since the limitation of this temperature is the main criterion for gearbox thermal rating. A temperature that is too high has the following impact (conforming to DIN 3996):

a) modifies the initial physical and chemical oil properties, hence shortening lubricant durability;
b) breaks down the additives in an accelerated mode;
c) destroys the seals prematurely.

Therefore the limitation in the design phase of the sump temperature remains a basic problem to ensure the normal operating of worm gearboxes.

2. Short view of the existent methods for worm gearbox thermal rating

A discussion of the main references in thermal worm gearbox calculus is given below.

Conforming to DIN 3996 [2], the calculus method is given for two lubrication cases: splash and forced feed. The following steps are valid for thermal calculus:

a) calculation of the total power loss composed by the friction power in tooth gearing, in idle running, in bearings and in seals;
b) deriving the sump temperature (for the case of splash lubrication; in the other case of the forced feed lubrication the oil temperature is controlled by cooling or flow);
c) calculation of the thermal safety factor, obtained by:
    - temperature in the case of the splash lubrication:

$$S_T = \frac{\vartheta_{s\,lim}}{\vartheta_S} \geq S_{T\,min}\,; \tag{1}$$

    - power in the case of the forced feed lubrication:

$$S_T = \frac{P_K}{P_V} \geq S_{T\,min}\,, \tag{2}$$

where: $\vartheta_{s\,lim}$ and ϑ_S are the limit and, respectively, effective temperatures of the sump oil; P_K and P_V - the cooling and, respectively, the total power loss in the worm gearbox; $S_{T\,min}$ - the minimal thermal safety factor (recommended 1.1).

Conforming to Niemann-Winter method [4] gives in addition a simplified empirical calculus method for transient operating conditions. The method is valid for a long pause in working:

$$t_{pause} \geq \frac{4\,a}{100}\ \text{[hours]}, \tag{3}$$

a being the center distance in mm. Finally the safety factor is compared with the one admissible for the specific transient operating conditions (empirical), using the formal expression (1).

Observations:

a) the transient operating conditions are not included in the DIN variant;

b) the treatment of the transient operating conditions in the thermal calculus is limited in the Niemann-Winter method.

3. Proposed calculus method for worm gearbox thermal rating

Generally the transient operating conditions can be very different. An example of variation in time of the exit torque of a worm gearbox is represented in the figure 1. The pause times are shorter than the ones imposed by the Niemann-Winter method for the similar thermal rating of the worm gearboxes.

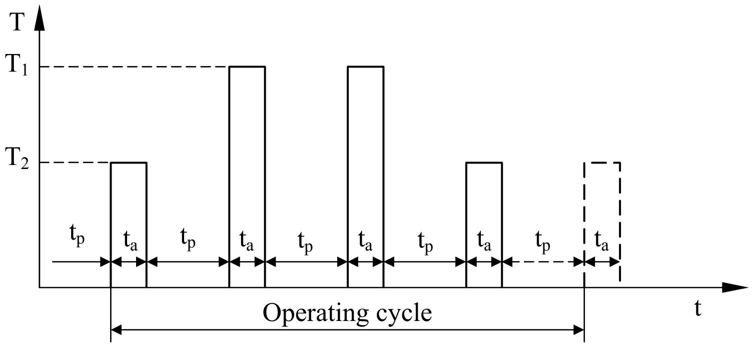

Fig. 1. *A cycle of the time variation of exit torque of a worm gearbox: T - exit torque;* t_a *- operating time;* t_p *- pause time.*

A specific method is proposed below for simulating operation under these conditions. The basic principle of the method is the consideration of the heat stored in the solid components and lubricant (oil). This method contains the following steps valid for a small time increment Δt:

a) calculation - using the indications, typical values of constants and expressions given in DIN 3996 [2] - of the total power loss P_V comprising friction power in tooth gearing and bearings, neglecting the power loss in idle running and in seals (very low about a lot of calculations); this power loss depends on the number of revolutions n which varies in transient operating conditions;

b) derive the heat quantity given out in the little time interval Δt in the operating conditions:

$$\Delta Q_i = P_{V,i} \cdot \Delta t \; ; \tag{4}$$

c) calculate the elements temperatures at the final time interval taking into account the specific heat and the mass of the components:

$$\vartheta_i = \frac{Q_{i-1} + \Delta Q_i}{m \cdot c} + \vartheta_{i-1}, \tag{5}$$

with m – mass of the element, c – specific heat of the material, ϑ_{i-1} - initial temperature;

d) determine the transferred heat quantity from an element to another at this final time increment;

$$\Delta Q_{transf\ 1-2} = k \cdot A \cdot \left(t_{i,1} - t_{i,2}\right); \tag{6}$$

e) determine the new temperatures of the elements after this heat transfer.

The steps mentioned above are repeated (iterated) for the following intervals Δt until the final working cycle.

During the pause time heat is not generated, but it is transferred between components because of their temperature difference. This is why the steps mentioned above must also be repeated for this pause time.

The rating criterion is checking of the thermal safety factor using the same expression 1, considering the admissible safety factor as value $S_{T\min} = 1.1$.

4. Application of the proposed method for worm gearbox thermal rating

The presented method was applied to the verification of a projected worm gearbox with discontinued working. Because the emplacement space is very limited, the gearbox must have small dimensions. The gear data are given in table 1 and their working cycle characteristics are presented in table 2. It is noted that between the effective work phases the worm gear remains in long pauses.

Table 1. Gearbox characteristics

Worm teeth number	**Worm-wheel teeth number**	**Axial modulus [mm]**	**Speed ratio**	**Worm speed [rot/min]**	**Centre distance [mm]**	**Housing position**
2	41	6.3	20.5	750	160	Horizontal

Table 2. Working cycle characteristics

Phase	1	2	3	4	5	6	7	8
Wheel torque [N·m]	302	0	592	0	592	0	302	0
Duration [min]	8	80	8	80	8	80	8	80

In figure 2 the structure of the heat producing and propagation process (simulated) is shown. Two principal heat sources exist here: the worm gearing and the bearings. The heat produced in the gearing will propagate firstly in the worm and wheel mass; through the contact area with the oil the heat subsequently propagates in lubricant and onward to the housing. The heat produced in the bearings is transferred to the housing and the worm gear. Because the heat conductivity of metals is very great compared to those of oil or of air, we can neglect the heat gradient in worm, wheel and housing.

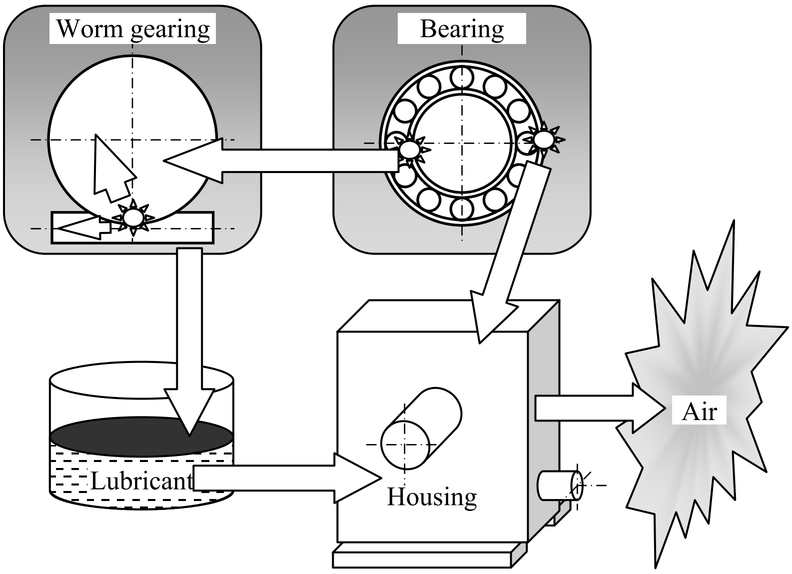

Fig. 2. Structure of the heat producing and propagation process that is simulated

For the thermal calculus, the following sizes are estimated using the indications given in DIN 3996 [2]:

a) the coefficient of friction between the worm and wheel is estimated, $\mu = 0.05$ (it results the gearing efficiency $\eta_{gearing} = 0.788$);

b) the global heat transfer coefficient between housing and environmental air, $k = 12$ W/m^2/K.

The friction power lost in rolling bearings was approximated (estimated) using a global efficiency for a pair of bearings of $\eta_{bearings} = 0.995$. The heat transfer coefficient between the oil and metallic components (housing, worm and wheel) is calculated using the following expression [3]:

$$k \approx 104 \sqrt[4]{\Delta\vartheta} \left[\mathrm{W/m^2/K}\right], \tag{7}$$

$\Delta\vartheta$ being the temperature in degrees difference between the oil and metallic components.

The other characteristics of the gearbox components that are used in the heat transfer simulation are given in the table 3.

The main results are represented graphically in the figures 3…6 and the table 4. One would see the following by the analysis of these results:

a) in accordance with the figure 3, the temperatures of the ensemble worm-wheel and of the oil during the operating phases increase very quickly, but the same size of the housing has a insignificant variation;

b) in accordance with the figure 4, the heat accumulated in the ensemble worm-wheel and in the oil is transferred to the housing very slowly (80 minutes), this phenomena determining the corresponding decreasing of the temperatures of the previous mentioned components. But the temperature of the oil increases firstly on a short time because of the heat accumulated in the ensemble worm and wheel. The housing temperature increases in the first time and after then it decrease slowly;

c) in accordance with the figure 5, the oil temperature has important variations on each operating and pause phase. The medium oil temperature increase firstly and after that it is stabilised in time (the temperature variations associated to the operating and pause phases became similarly);

d) in accordance with the figure 6, the housing temperature increases quickly in the beginning and after this it varies slowly.

Table 3. Elements characteristics used for the heat transfer simulation

Element	Heat transfer area [m^2]	Massis [kg]	Specific heat [J/kg/K]
Worm	0.063	12.2	506
Worm wheel	0.086	26.2	500 (pond rated)
Oil	It is given to the other elements	2.6	1988
Housing	With the oil: 0.35	99	540
	With the air: 0.65		

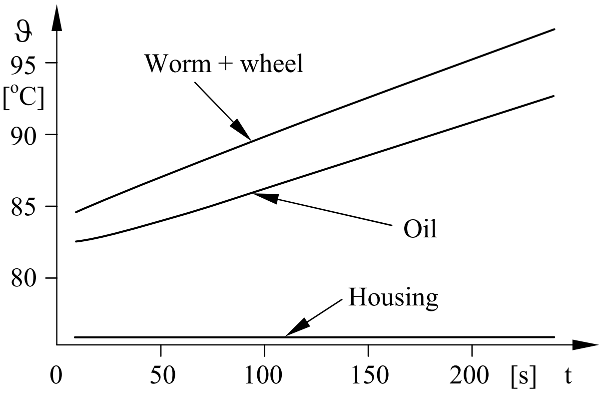

Fig. 3. Evolution of the temperature in operating phase

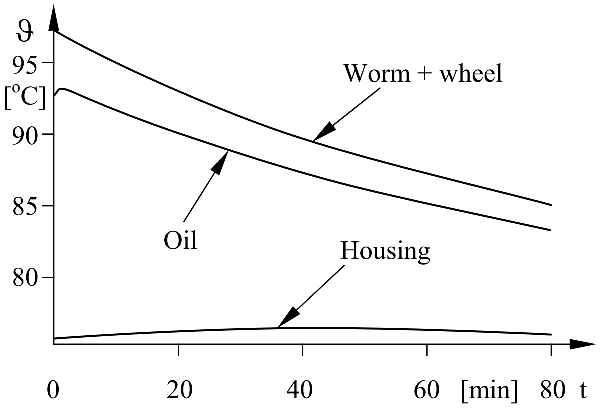

Fig. 4. Evolution of the temperature in pause phase

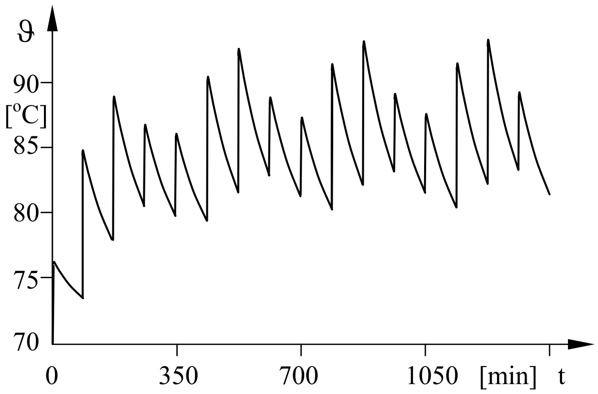

Fig. 5. *Evolution of the oil temperature during 4 operating and pause cycles given on the fig. 1*

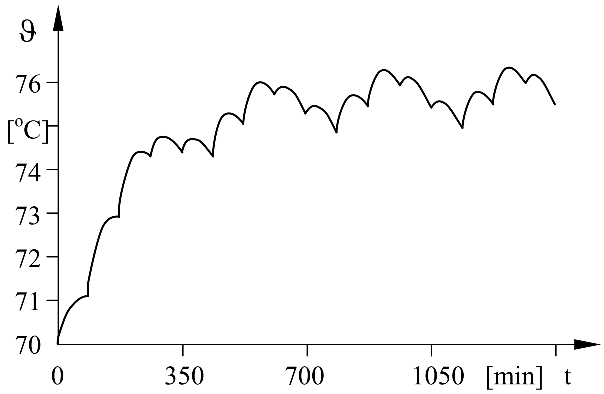

Fig. 6. *Evolution of the housing temperature during 4 operating and pause cycles given on the fig. 1*

Table 4. Values of the component temperatures at the final of each operating or pause phase

Operating cycle	**Components**	**Operating or pause phases of the cycle**							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
		Temperature [^{o}]							
1	Worm and wheel	78.2	74.1	87.9	79.1	92.6	81.9	89.5	80.9
	Oil	75.9	73.4	83.9	77.8	88.2	80.4	86.1	79.6
	Housing	70.1	71.1	71.3	72.9	73.1	74.3	74.4	74.4
2	Worm and wheel	88.6	80.5	94.1	83.1	96.4	84.4	91.9	82.5
	Oil	85.4	79.3	89.6	81.5	91.8	82.8	88.4	81.1
	Housing	74.4	74.3	74.4	75.1	75.2	75.7	75.7	75.3
3	Worm and wheel	90.1	81.6	95.	83.7	97.1	84.9	92.3	82.8
	Oil	86.8	80.2	90.5	82.1	92.4	83.1	88.8	81.3
	Housing	75.3	74.9	75.	75.4	75.5	75.9	75.9	75.4
4	Worm and wheel	90.4	81.7	95.2	83.8	97.2	84.9	92.3	82.8
	Oil	87.	80.4	90.7	82.2	92.5	83.2	88.8	81.4
	Housing	75.4	75.	75.	75.5	75.6	76.	76.	75.5

5. Conclusions

- The gearbox operation can be intermittent and with long pauses between the working periods.
- The thermal calculus for transient operating conditions is not presented in full in the technical literature. Niemann-Winter [4] develops an approximate method for this special thermal calculus.
- The main characteristic of the method proposed in the present paper is the estimation of the sump temperature in time, since the limitation of this temperature is the main criterion for gearbox thermal rating.
- The estimation of the temperature variation of each component (worm, wheel, oil, housing, air) takes in consideration the heat transfer and accumulating in these components, with the neglect of the heat gradient in worm, wheel and housing.

- The proposed method contains steps of calculus valid for a small time increment.
- The results offered by an application show that the temperature variations of the worm, wheel and oil are very important in time in comparison with the one of the housing.
- A practical conclusion: the operating intermittent regime with long pauses permits the designing of the corresponding gearboxes with small size, because the heat is stored in components and transferred gradually to the ambient environment.

References

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