Load Distribution in Planetary Gears

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Introduction

Two-shaft planetary gear drives are power-branching transmissions, which lead the power from input to output shaft on several parallel ways. A part of the power is transferred loss-free as clutch power. That results in high efficiency and high power density. Those advantages can be used optimally only if an even distribution of load on the individual branches of power is ensured. Static overconstraint, manufacturing deviations and the internal dynamics of those transmission gears obstruct the load balance. With the help of complex simulation programs, it is possible today to predict the dynamic behavior of such gears. The results of those investigations consolidate the approximation equations for the calculation of the load factors $K_\gamma K_v$ and $K_{H\beta}$.

Parameter Study on Load Factors

The calculation of the operational dynamic behavior of a planetary gear stage is done with the 3-dimensional simulation program SIMPLEX, which was developed in an earlier research project (Ref. 2). The program is able to describe all masses within the transmission with six degrees of freedom each and considers the influence of the mentioned disturbances on the masses' dynamics. The dynamic model underlying the program is shown in Figure 1.

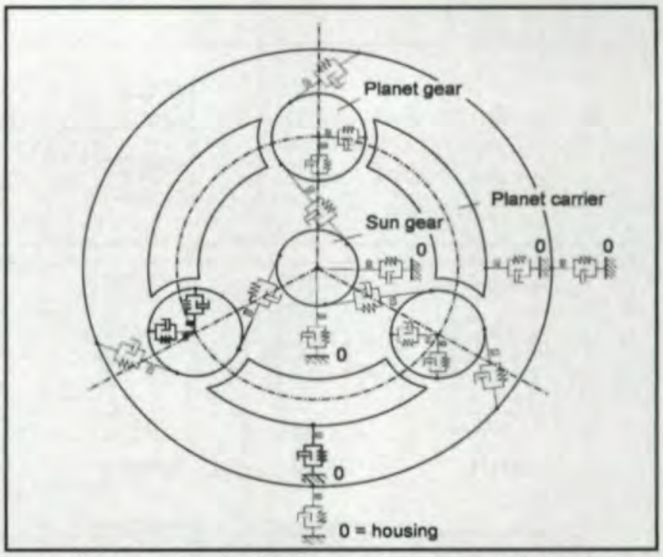

Fig. 1—Dynamic model of a planetary gear stage in transverse section.

Afterwards, the masses are linked to the bearings and to the foundation by discrete, elastic shock-absorbing elements. Table 1 quotes the parameters, which were considered on the dynamic simulation.

Table 1—Parameters considered on the dynamic simulation.

Environmental conditions: Attached mass inertia Stiffness of attachment Line load Speed of sun wheel Relative circumferential velocity	**Size and geometry of the gearing:** Center distance Gear ratio Number of planet gears Sum of the addendum modification Face width/diameter coefficients Number of teeth of sun Base helix angle
Tooth correction: Crowning Tip modification Long addendum teeth	**Gear tooth quality:** QF_p, Qf_p, $Qf_{H\beta}$ Pitch tolerance of the planet carrier Bearing eccentricity Bearing clearance of planet gears Angle of position of the planet gears

The single elements are combined in nine different types of planetary gears, for which the parameter study gives the required load factors. The planetary gears are categorized according to the designations of the first column of Table 2. Thus, for example, a transmission with a sun gear shaft and a housing-fixed internal gear receives the designation "S1H1." That transmission version forms the basis for the parameter variation. All other transmissions provide the

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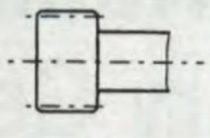
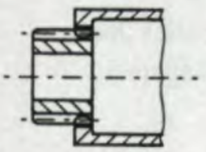
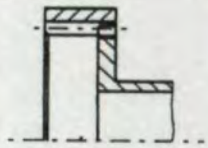
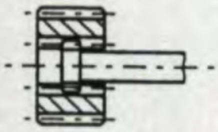
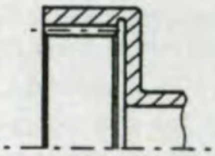
Table 2—Construction design of sun and ring.

Var.	Description	Scheme	Var.	Description	Scheme
S1	Sun gear		H1	Housing-fixed ring gear	
S2	Sun wheel with circumferential engaging curved-tooth gear coupling		H2	Ring gear with internal engaging curved-tooth gear coupling	
S3	Sun wheel with internal engaging curved-tooth gear coupling		H3	Ring gear with flange connection	

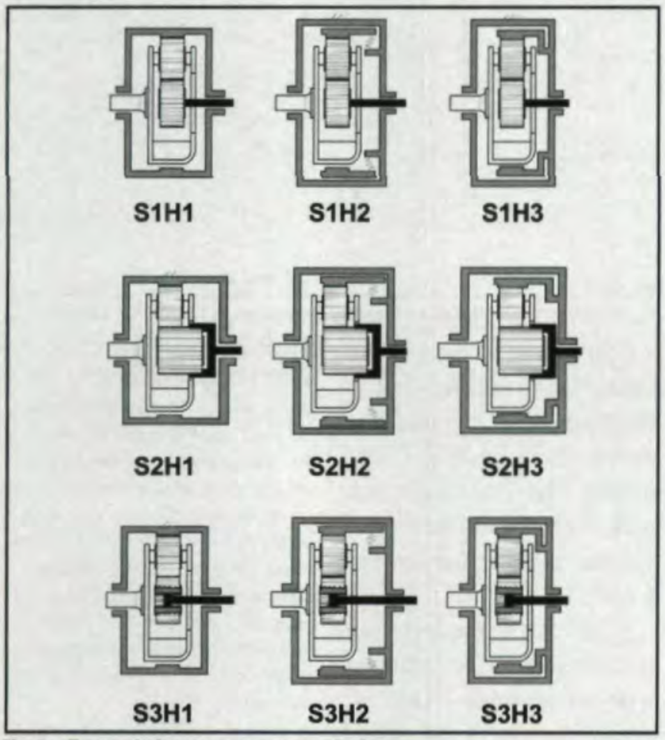


Fig. 2—Types of planetary gear transmissions.

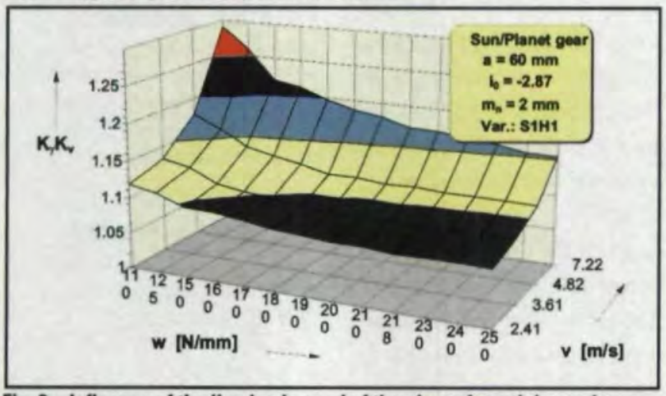


Fig. 3—Influence of the line load w and of the circumferential speed v on the factor product $K_\gamma K_v$ in the engagement of sun and planet gear.

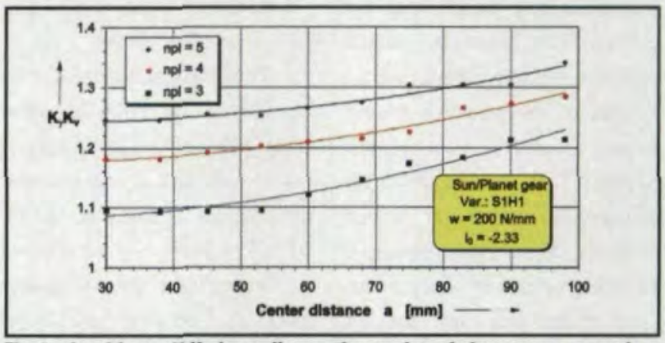


Fig. 4—Load factor $K_\gamma K_v$ depending on the number of planet gears n_{pl} and on the center distance a, shown for the engagement of sun and planet gear.

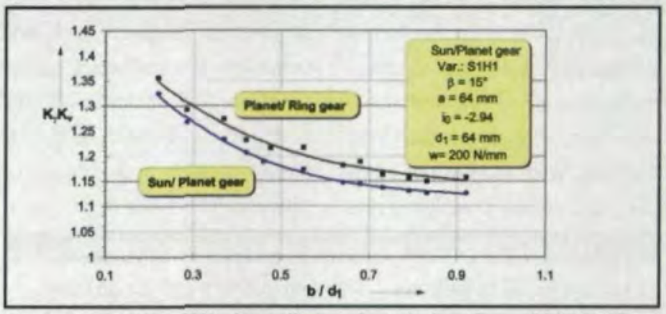


Fig. 5—Load factors $K_\gamma K_v$, depending on the ratio from face width b to diameter d_1 of the sun wheel.

influences of the examined parameter field.

***Influences on the load factors* $K_\gamma K_v$.** The following results were achieved by a parameter study with the program SIMPLEX. It shows the generally valid tendencies that a modification of the single parameters according to Table 1 has on the tooth load conditions as mentioned above. Those tendencies are represented for a basic S1H1 transmission, according to Figure 2. The indicated values of the load factors apply to the transmission specified in the respective picture. The load factors, achieved by transmissions of other geometry or type of construction, can be determined by approximating equations, contained in Reference 1. The results apply to gears of DIN quality class 6.

All rolling bearings indicate a bearing clearance of class CN.

Figure 3 shows the influence of the specific load w for different peripheral speeds v on the dynamic behavior of the transmission.

The distribution of the load on several planet gears permits a higher throughput of power. Figure 4 shows the influence of the associated increasing static overconstraint and the influence of the phase position of the engagements at the circumference of the coaxial gears, dependent on the number of planet gears.

Figure 5 shows the effect of a changed face width b on the value of the load factors $K_\gamma K_v$. The basis of all calculations is a constant line load w, which corresponds to an increase of the outside torque with rising face width. The improvement of the dynamic behavior with an increasing face width does not result from the modified geometry, but from the risen load level.

The quality of gear production is crucial for the level of the dynamic excitations in the transmission. Both the total pitch variation F_p and the individual pitch variation f_p indicate a clear influence on the load factors.

Influences on the load factor $K_{H\beta}$. A misalignment of the axles causes a system-dependent inclination of the gears. For that reason, an increase of the effective tooth trace variation $f_{H\beta}$ can generally be expected. Figure 7 shows the dependence of the factor $K_{H\beta}$ on the quality of the tooth trace angle variation $f_{H\beta}$. In both engagements of the planet gear, a significant rise of the factor $K_{H\beta}$ is to be observed, already starting from DIN quality class 4. The housing-fixed ring gear of the basic version S1H1 causes a partial adjustment of the planet gear in reference to the ring gear, which results in a more favorable face width load distribution. Accordingly, the values of the factor $K_{H\beta}$ of the engagement planet/ring gear are lower than those of the engagement of sun/planet gear.

Figure 8 shows an increase of the factor $K_{H\beta}$ in the S1H1 version, which depends on the number of the engagements of sun/planet gear.

Approximation equations for the factor product $K_\gamma K_v$ ***and the factor*** $K_{H\beta}$. An important result of this research project is approximation equations for the determination of the load factors $K_\gamma K_v$ and $K_{H\beta}$. Detailed information is given in Reference 1.

Testing

A system of coupled, inhomogeneous, non-linear, second-degree differential equations describes the dynamic behavior of an idealized planetary gear. The solution of that system of differential equations provides the displacements of the geometrical centers of the sun/planet gears and of the planet carriers in the plane of transverse section. A comparison of the calculated and the measured axis shift allows for the control of the simulation program.

The measurements are taken at the self-adjusting transmission elements. Their movements can be registered with contact-free working displacement transducers. Two horizontally and two vertically attached displacement transducers determine the misalignment of the transmission elements. The mounting

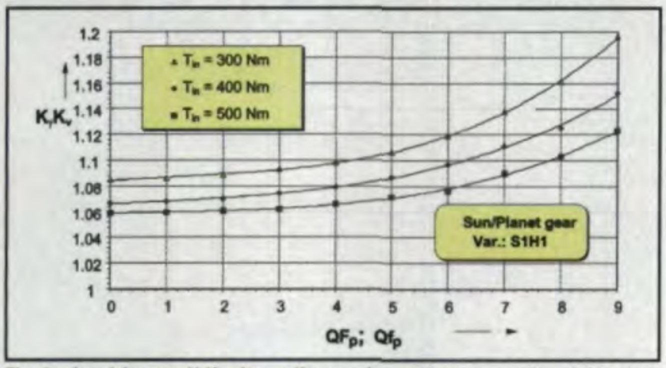


Fig. 6—Load factors $K_\gamma K_v$, depending on the production quality of the pitch variations.

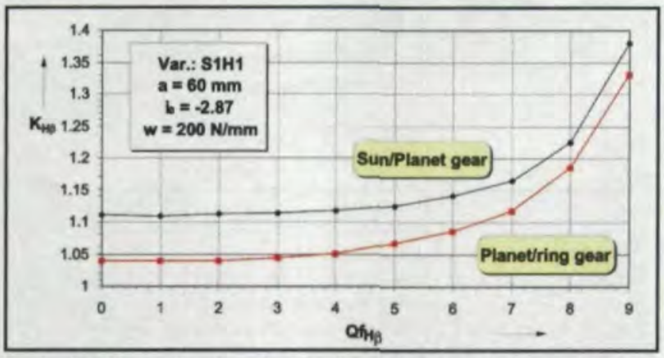


Fig. 7—Load factor $K_{H\beta}$ dependent on the quality of tooth trace angle variation $Qf_{H\beta}$, shown for the engagement of sun/planet gear and planet/ring gear.

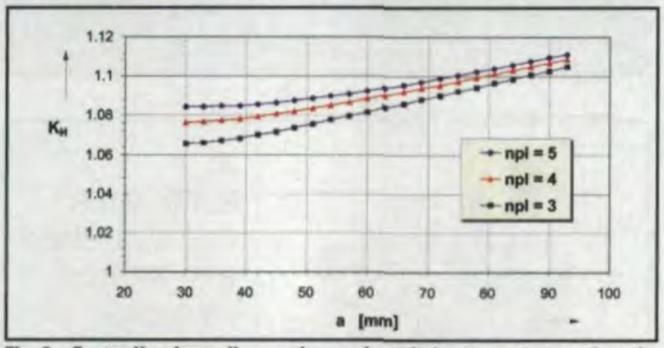


Fig. 8—Factor $K_{H\beta}$ depending on the number of planet gears n_{pl} and on the center distance a, shown for the engagement of sun and planet gear.

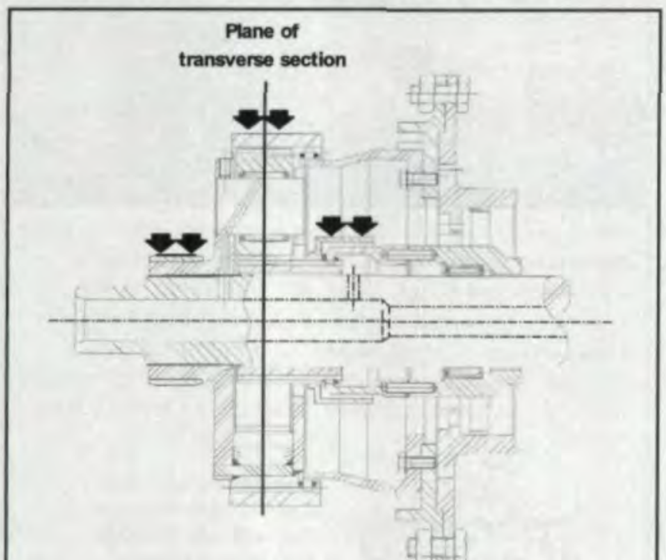


Fig. 9—Section of the S2H2 test transmission. The position of the displacement transducers is marked by arrows.

arrangement of the displacement transducers can be seen in Figure 9.

Reference 1 compares calculation and measurement and discovers a good correspondence between the respective values.

Notes for the Technical Designer

Based on recent findings of projects concerning load distribution in planetary gears, the following notes for design can be recorded:

1. With the rising extent of utilization of the transmissions, the dynamic effects lose some of their importance. Caused by a high line load, the ability of self-adjustment of the gears improves due to existing degrees of freedom and due to elasticity. The factors $K_\gamma K_v$ and $K_{H\beta}$ decrease with rising load.
2. An increasing circumferential velocity, on the other hand, shows opposite tendencies regarding the load balance. High-speed transmissions usually show very high load factors, especially when operated on low load levels.
3. Gearing deviations, such as F_p, f_p and $f_{H\beta}$, if toleranced according to DIN quality class 6 or better, only exert a small influence on the dynamic behavior of the transmission. Starting from DIN quality class 6, it is advisable to provide crowning or end relief.
4. Center distance deviations, tolerated according to DIN 3964, remain without influence on the load factors, as long as there is still some backlash existing. However, if the backlash is consumed, the loads can achieve several times the nominal values.
5. Large numbers of planet gears increase the degree of static overconstraint of the transmission. In order to select the number of planet gears, the gain at load carrying-capacity as a result of power branching has to be compared to the losses resulting from increased dynamic excitation.
6. The load factors $K_\gamma K_v$ of spur gear transmissions can be up to 10% higher than with comparable helical gearing transmissions.
7. For center distances less than 100 mm, no influence of size on the load distribution—or more precisely on the load factors $K_\gamma K_v$ and $K_{H\beta}$—could be determined. O

References

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