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Turbo planetary gear units: State of the technology

Turbo planetary gear units have been in use in systems powered by high-speed turbo machines for over 50 years. Today's units are capable of transmitting up to 40 MW. Despite their compact design, high efficiency and outstanding reliability, they have yet to find the popularity that, with their benefits, they deserve. The aim of this paper is to present the current state of the technology of turbo planetary gears and highlight their advantages to users.

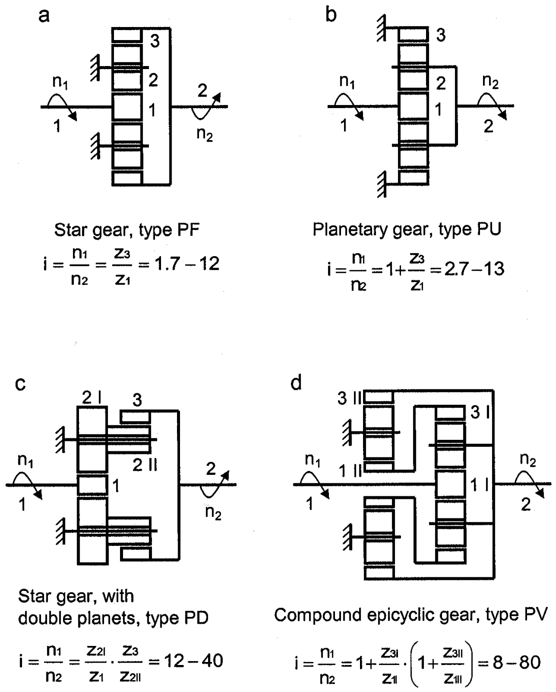
1 Introduction

Because power is divided over several tooth meshes, planetary gear units are smaller than their conventional counterparts. This in turn results in a more advantageous power-weight ratio and – by virtue of the lower peripheral speeds – improved efficiency. The smaller gear diameters produce smaller mass moments of inertia, which substantially reduces the acceleration and decelerating torques during acceleration and braking. The coaxial design permits a more compact and therefore cheaper base plate. This saves floor space and building volume, a vital consideration for installations such as mobile generator sets for transport in standard containers.

2 Variants

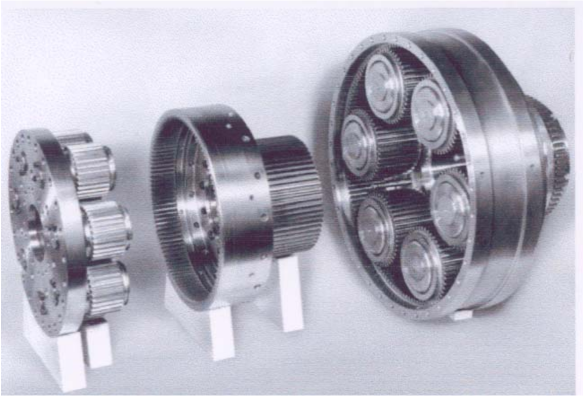
The theoretical influences affecting power flow and speed ratios have been extensively discussed in the literature [1, 2]. In principle, a planetary gear unit consists of three coaxially rotating components: a sun gear, a carrier with several planetary gears and the ring gear. Figure 1 shows the four preferred variants for turbo gears.

Types PF and PU have a similar ratio range. Type PF is used when the rotating carrier would cause unacceptably high pressure on the bearing journal.

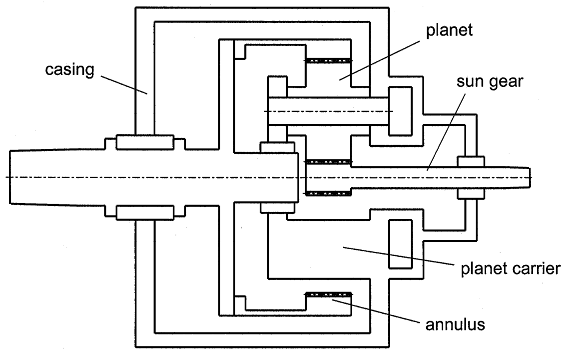


1: Turbo planetary gear unit variants

With type PU it is necessary to take account of the relatively high windage. Type PV is used in its lower ratio range in cases where the external diameter of the gear unit has to be as small as possible – for example if the gear unit has to be incorporated into the turbine housing. Part of the power to be transmitted in stage I is conducted directly through the carrier into shaft 2. As a result stage II only needs to be constructed for the differential power P II. Figure 2 shows such a gear set. It transmits the power generated by a gas turbine (4000 kW at 12,000 rpm) to a generator (1500 rpm).



2: Gear set of a type PV power divider gear unit



3: MAAG approach to a type PF turbo planetary gear unit

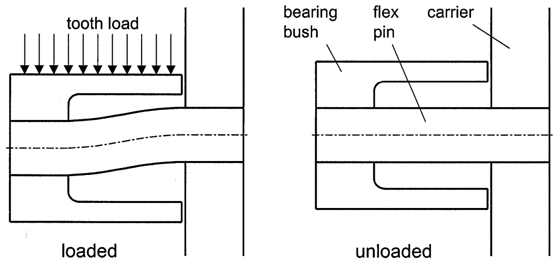
3 Load balance

Optimum power division is possible only if the load is distributed as evenly as possible across the individual planet gears. Using distribution systems – single- or double-jointed tooth couplings – creates major disadvantages. The frictional forces that occur in the couplings during distribution generate retaining moments that cause tooth alignment errors between the tooth flanks. An uneven load balance with damaging compression across the edges occurs. Totally centred tooth loading would only be possible with completely friction-free mounting, something which is impossible to achieve in practice. Load balancing systems are impotent against dynamic interference such as that caused by pitch errors. The mass inertia of the gear unit elements, particularly the ring gear, means that they cannot be momentarily shifted into the balanced-load position. A further disadvantage becomes apparent when the gear unit is running at rated speed and with no load, for example in a generator plant prior to synchronization. The gear unit system, consisting as it does of several backlash-laden joints and large masses, is unable to centre itself and behaves unstably.
MAAG's solution to this problem can be summarized as follows:

- maximum manufacturing precision
- free self-adjusting pinion
- careful selection of ring gear elasticity

MAAG does not use joints for power distribution, but the elasticity and accuracy of its gear unit components. Figure 3 gives a diagrammatic representation of the MAAG approach.

If there is no friction there can be no retaining moments and no wear. If there is no backlash there can be no additional dynamic forces. All rotors are statically determinate in all operating states. The ring gear is mounted and centred by two radial bearings, the comparatively light pinion centres itself between the planet gears even when only under a slight load. The ring gear has an integral connection in the form of an elastic, thin-walled hollow cylinder. As a result, strength-reducing bolt holes in the body of the ring gear are eliminated.
A further elegant and effective solution is to provide elastic mountings for the planet gears in the form of flex pins (Figure 4). These bend in an S-shape when under load, with the result that the planet gears do not skew but are simply minimally displaced parallel to the pinion or ring gear axis. They ensure an optimum load balance between the meshed teeth and even load distribution across the entire width of the tooth face at both full and partial load. The planet gears shown in Figure 2 are mounted on flex pins. MAAG has been using this solution for many years – even in its marine gear units. More recently, we have been using them in gear sets for wind turbines.



4: Principle of the flex pin

4 Gearing

4.1 Choice of gearing

The key factors influencing the choice of the most suitable gearing are load capacity, efficiency and the available production options. Each of the three possible systems – spur gearing, single helical gearing and double helical gearing – has its advantages and disadvantages.
Spur gears slide axially towards each other, generate no axial forces and require no axial bearings. An important operating benefit is the fact that the pinion can be removed for inspection without having to completely dismantle the entire gear unit.
If single helical gearing is used, the two opposing axial forces acting on the planet gear generate a large tilting moment, which necessitates wide bearing supports and substantial bearings. Furthermore, axial bearings have to be fitted to the pinion and ring gear, and these substantially diminish gear unit efficiency.
Double helical gearing requires free axial adjustability to achieve even load distribution across the two tooth halves. However, the multiple meshes prevent the necessary movement. In addition, external axial forces may interfere with load distribution. The slightly better efficiency compared to spur gearing is an advantage.

4.2 Tooth modifications

A tooth mesh may be said to have optimum kinematics when both teeth have the same basic pitch. However, since the pinion gets hotter than the planet gears, its base circle – and therefore base pitch – expand. During manufacturing in cold condition, the pinion has to be made with a pitch that has been reduced by the difference due to expansion. The increase in pitch of the rotating ring gear as a result of centrifugal force is also taken into account during manufacturing.
Longitudinal modifications compensate for the mechanical torsion of the pinion and, if flex pins are not used, of the carrier. There is no deflection. Heat is distributed unevenly across the width of the tooth face, resulting in uneven expansion of the gear body. In such cases, the tried-and-tested MAAG asymmetrical concave lead modification comes into its own. The methods used to calculate the negative crown are derived empirically from many years of observing contact patterns at rated load [3].
Suitable profile correction is intended to achieve two goals:

- To eliminate mesh impact and shock loads at the beginning and end of meshing and the transitions from single to double meshing.
- To achieve uniform transmission of rotary movement despite heavy, tooth position-dependent tooth deformation.
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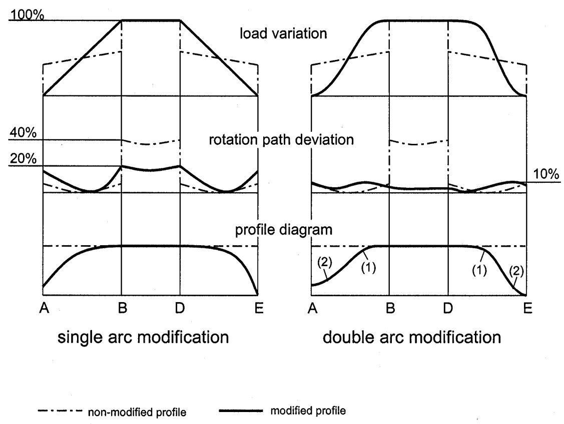
The primary objective, therefore is to minimize additional dynamic loads and gear unit noise.

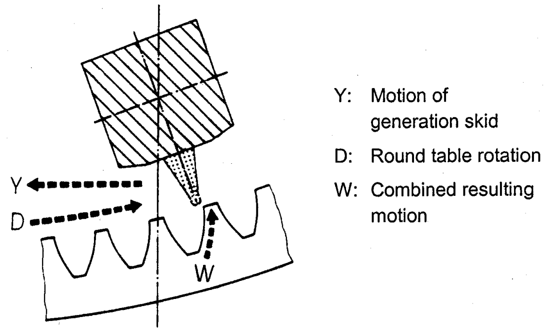


5: Single and double arc correction

A trapezoidal load curve along the transverse path of contact A – E and a halving of the deviation in angle of rotation can be achieved with the widely known single arc correction (Figure 5a). One disadvantage remains, however: The normal of contact does not run through the pitch point at the beginning and end of contact, a phenomenon that is equivalent to a momentary change in ratio. MAAG goes the decisive step further here. A second, external arc (2) is attached tangentially to the first internal arc in such a way that it ends normally to the line of action [4]. Using this double arc correction (figure 5 b), load curves with constant transitions and relative rotary errors of less than 10% are achieved. As a result, it is possible to construct an extremely smooth-running spur-geared planetary gear unit – provided that appropriate production facilities are available.

4.3 Manufacturing

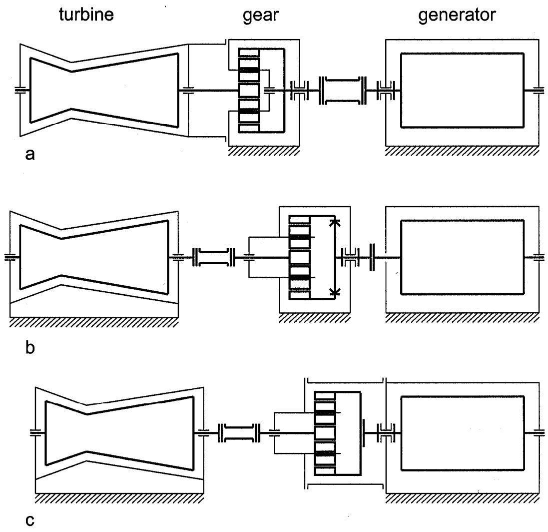
While the pinion and planet gears are always ground, there are currently three ways of finishing the internal gearing of the ring gear: shaping, grinding to shape (in which the profile of the grinding wheel is transferred to the tooth flank) and precision single-point tooth-cutting (Figure 6). The latter method was developed by MAAG and involves generating the tooth flank by a rolling movement. Using this method avoids profile errors of the sort that are inevitable with grinding to shape. Since the process also permits optimum fillets, it minimizes fillet bending stresses and in turn makes possible the elastic design of the ring gear mentioned in section 3.



6: Principle of precision single-point tooth cutting as applied to internal gearing

5 System designs

There are several ways of integrating the planetary gear unit into the final system. The following three examples are based on gas turbine-driven power generation plants (Figure 7 a, b and c).
Figure 7a: The gas turbine is attached directly to and supported by the gear unit housing. If turbine and gear unit both display sufficiently low axial and radial run-outs, the coupling shaft between the turbine shaft and gear unit input shaft can be omitted. The generator is mounted separately and connected to the gear unit by a double-jointed coupling. This is necessary because the different heat-induced expansions of the gear unit and generator housing cause relative shifts in the shaft positions. The gear unit output shaft has to be supported by two radial bearings.

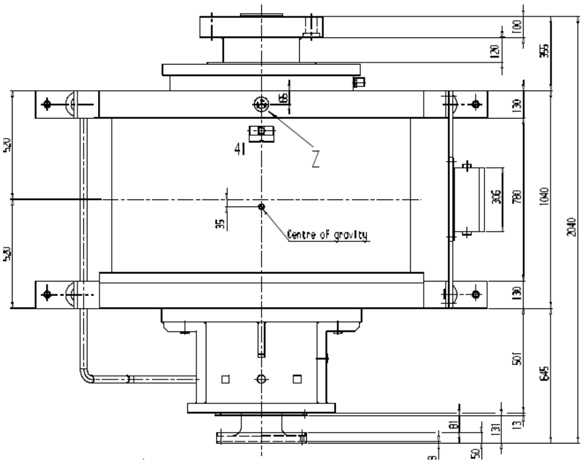


7: Different power generation plant designs

Figure 7b: The gas turbine, gear unit and generator are all installed separately. Since radial shifts occur between the turbine shaft and gear unit input shaft, a double-jointed coupling is required. The support bearing on the pinion prevents unstable running, especially when the train is running at rated speed with no load. The generator shaft (rotor) is connected rigidly to the gear unit output shaft and the first generator bearing is incorporated in the gear unit housing. As a result, the different heat-induced expansions of the gear unit and generator housing produce no radial shift. They do, however, cause an angle error between the rotor and ring gear axis, but this can be absorbed by a single-jointed coupling.
Figure 7c: In the third design the gear unit is attached directly to the generator housing. The ring gear is an integral part of the rotor. Since no radial or angle shifts can occur, no clutch joint is required.
Each system has its own individual requirements. By collaborating closely with the system builder to develop the ideal gear solution, gear unit manufacturers can help to obtain maximum cost-efficiency and reliability from the system as a whole.

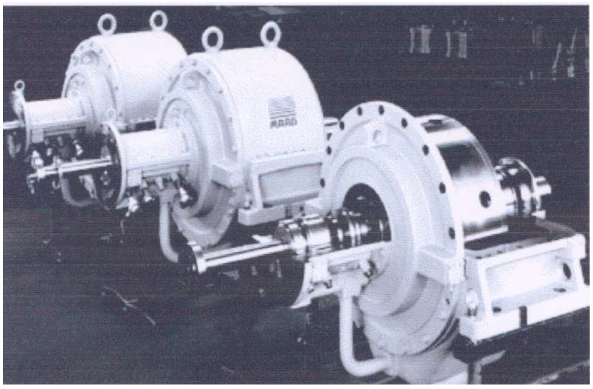
6 Example applications

The most powerful turbo planetary gear unit currently in service in the world is the GPF5-34 (Figure 8), which transmits the 37,000 kW produced by a Rolls-Royce RT62 gas turbine to a generator. The gear unit incorporates an integral generator bearing.



8: GPF5-34 turbo planetary gear unit

An example drawn from compressor applications is the TPF3-19s, which is used as a step-up gear unit between an electric motor and centrifugal compressor (Figure 9). Output: 2650 kW. Speeds: 1485/13500 rpm. The compressor shaft is rigidly connected to the pinion. The axial bearing that absorbs the compressor's axial thrust is incorporated in the gear unit.


9: TPF3-19s turbo planetary gear unit for compressor- drive

7 Summary

Turbo planetary gear units permit a coaxial and therefore space-saving installation of engine and machine. Elastic, backlash- and friction-free gear unit elements ensure an ideal load balance. High manufacturing accuracy and advanced tooth flank modifications guarantee quiet and reliable operation.

Literature:

[1] MAAG Gearbook, 1990

[2] Müller, H.W.: Die Umlaufgetriebe. Auslegung und vielseitige Anwendungen. Springer-Verlag, Berlin 1998

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[4] Bronner, H.-J.: Einfluss von Flankenkorrekturen auf Zahnkraft und Verformung bei Geradverzahnung. Dissertation, TH Stuttgart, 1980