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SOME CONSIDERATIONS ON THE APPLICATION OF WOLFROM PLANETARY GEAR TRAINS

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Abstract. *In engineering it is sometimes necessary to achieve very precise regulation with immediate lockdown of the regulated element in the desired position, or to achieve a very high reduction ratio in a confined space. For example, such needs arise in the design of reduction gear for the operation of valves, construction hoists, and constant speed propellers. A Wolfrom planetary reduction gear seems to cater for all these needs by providing high reduction ratios in a single stage, and even becoming self – locking in certain designs. The purpose of this article is to offer an insight into the design and operation of Wolfrom planetary gear trains. The efficiency of a Wolfrom gear train is discussed, as well as the advantages and disadvantages of their use. An overview of current applications is given and the prospects for future applications discussed, with remarks being given about the selection of planetary gear trains adequate for the intended application.*

1 INTRODUCTION

In engineering it is sometimes necessary to achieve very precise regulation with immediate lockdown of the regulated element in the desired position, or to achieve very high reduction ratios in confined spaces.

For example, reduction gear for the operation of large butterfly valves must provide some 90° of circular motion while having to develop a very large torque. Additionally, the gear train must be as compact as possible, and be able to stop as soon as power is turned off. The assembly might operate in damp conditions, or underwater, so an external brake might not be feasible.

Construction yards use temporary power connections, while machinery is often connected using low power capacity links. Therefore, small construction hoists must be able to lift relatively large loads while being powered by relatively small electric motors, and have the ability to self lock in the occasion of power failure, while being as simple as possible to maintain and operate.

Constant speed propellers need to be locked down to the desired pitch position as soon as power is removed from the adjusting motor, and have a very large stepless span of settings.

Naturally, in all applications where the reduction gear must be as small as possible, a planetary gearset is preferred, as it has the additional advantage of the input and output shafts being coaxial.

From all the possible planetary gear combinations, a Wolfrom planetary gearset seems to cater for all these needs by providing high reduction ratios in a single stage, and even becoming self – locking in certain designs.

2 THE WOLFROM PLANETARY GEARSET

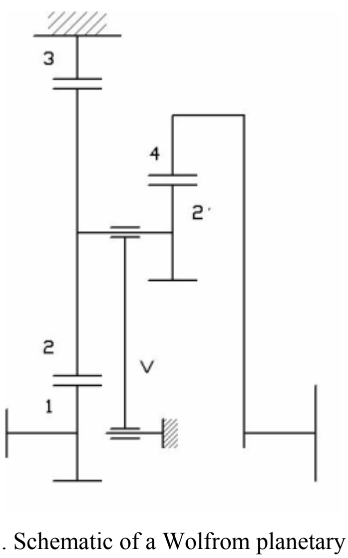

Figure 1. Schematic of a Wolfrom planetary gearset.

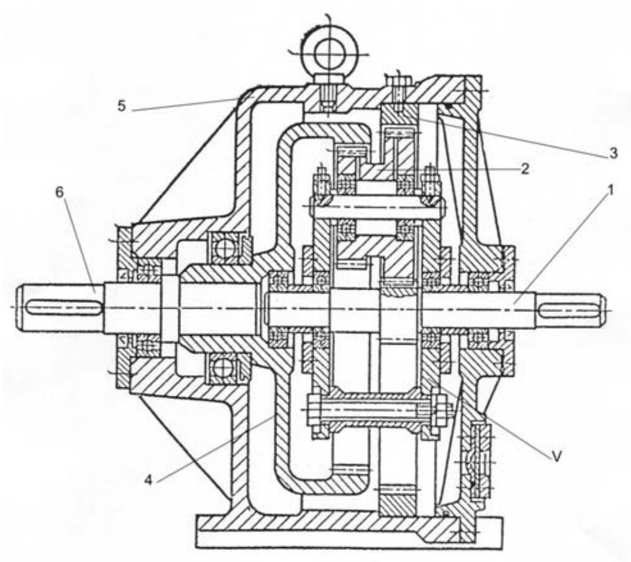

Figure 2. Cross section of a Wolfrom gearset. Notice input shaft with sun gear 1, planets 2 machined as one piece, annulus gear 3 bolted to casing 5, planet carrier v, internal gear 4 and ouput shaft 6.

A Wolfrom planetary gearset consists of the sun gear 1, planet gears 2 and 2' connected by a common shaft, planet carrier v, annulus gear 3, and internal gear 4 (Figure 1). The annulus gear is locked, and is usually either machined into the gear train housing or attached to it permanently.

A cross section of a Wolfrom gearset is shown in Figure 2. Some design features should be noted here – the planet gears are usually machined as one piece instead of being machined as separate parts connected by a shaft. Additionally, such a configuration allows for easy bearing of the planet carrier v.

Power input is by means of the sun gear 1, while power output is via the internal gear 4. The planet carrier v is free to rotate upon its pivot point and transmits no power.

The transmission ratio of the gearset was determined using the graphoanalytical method described in [1], and equals

$$i = \frac{\frac{Z_3}{Z_1} - 1}{\frac{Z_3}{Z_2} \cdot \frac{Z_{2'}}{Z_4} - 1}, \tag{1}$$

where Z_i (i = 1…4) is the number of teeth of the respective gear. The efficiency of a single stage Wolfrom gearset can be determined using the relations given in [2], with respect to the teeth number of gears:

$$\left(Z_{2'}Z_3 > Z_4Z_2\right) \rightarrow \eta = \frac{1-\left|\frac{Z_3}{Z_1-Z_3}\left(\frac{1}{\eta_{23}\eta_{12}}-1\right)\right|}{1+\left|\frac{-Z_{2'}Z_3}{Z_4Z_2-Z_{2'}Z_3}\right|\left(\frac{1}{\eta_{23}\eta_{42'}}-1\right)}, \tag{2}$$

$$\left(Z_{2'}Z_3 < Z_4Z_2\right) \rightarrow \eta = \frac{1-\left|\frac{Z_3}{Z_1-Z_3}\left(\frac{1}{\eta_{23}\eta_{12}}-1\right)\right|}{1+\left|\frac{-Z_{2'}Z_3}{Z_4Z_2-Z_{2'}Z_3}\right|\left(1-\eta_{23}\eta_{42'}\right)}, \tag{3}$$

where η_{ij} (i, j = 1…4) is the efficiency of the mesh between the respective gears. It can be assumed that the efficiency of an external mesh equals to η_{ij} = 0,98, and that the efficiency of an internal mesh equals to to η_{ij} = 0,99.

A Wolfrom gearset is generally designed for reduction ratios of i = (14) 16…800 (1600) in a single stage. According to data in [1], a gearset with a ratio of i = 16 would have an efficiency of 91%. Efficiency is inversely proportional to the transmission ratio, and drops to just 57% for i = 180.

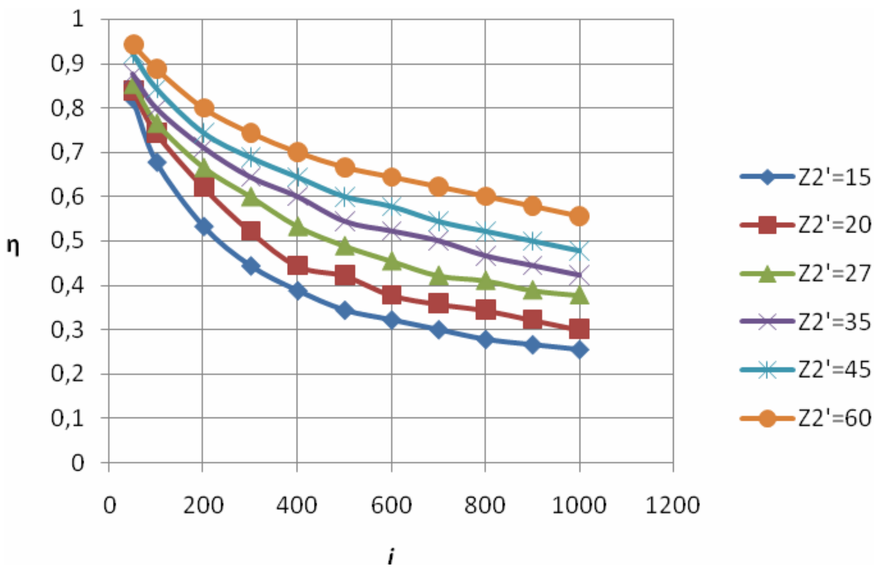

Figure 3. Efficiency chart of Wolfrom single stage units in relation to the teeth number Z2’ and the transmission ratio according to [1].

It is worth mentioning that any transmission with efficiency of 50% or less is considered self-locking. However, transmissions with efficiencies of around 50% or less are not suited to continuous running due to the amount of heat generated, and the extreme heat degradation of the lubricant which could result.

On the other hand, in regulation applications and intermittent running, self-locking can be a valuable asset, as the output shaft stops as soon as power is cut to the drive, and an additional brake mechanism can be disposed of, as the output shaft cannot be rotated by the load, which is quite convenient in the design of small and inexpensive hoists.

The gears 2 and 2' share a common shaft, or can even be manufactured in one piece, and the usual rules for the design of planetary gearsets apply, meaning that the size of the planetary gear 2' and the corresponding internal gear 4 is determined by the size of the gears 1, 2 and 3.

It should be mentioned that the efficiency of a Wolfrom drive greatly depends upon the selection of the teeth number of the planetary gear 2'.

2 SOME APPLICATIONS OF WOLFROM GEAR TRAINS

2.1. Constant speed propellers

The operating efficiency of an aircraft propeller depends on a number of factors, and is described by the equation [3]:

$$\eta_P = \frac{F_T \cdot v}{T_{PM} \cdot 2 \cdot \pi \cdot n} \tag{4}$$

where F_T is the thrust developed by the propeller, v the axial speed of the propeller, T_{PM} the resistance torque the propeller opposes to the prime mover, and n the number of revolutions per second of the propeller.

According to this equation, it is most desirable to operate the propeller at a constant number of revolutions, and provisions must be made to compensate for variations in aircraft speed.

A propeller in operation can be compared to a bolt following its thread through a nut. Now, assuming that the bolt revolves at a constant speed, it will travel at a higher linear speed if the pitch angle becomes coarser, and a slower speed for a finer pitch angle.

The same principle applies to propellers, and the system also allows for propeller feathering and reverse thrust braking. Aircraft engine design is simplified too, because the prime mover can be designed with a narrow operating range in mind.

Most constant speed propeller assemblies are operated by hydraulic power using either engine oil pressure or a dedicated hydraulic circuit. The downsides of this approach are its complexity, the need for accurate machining and sealing of oil ducts built into the gearbox output shaft, and the exposure of internal parts to combustion byproducts if the engine lubrication circuit is used as a source of hydraulic pressure.

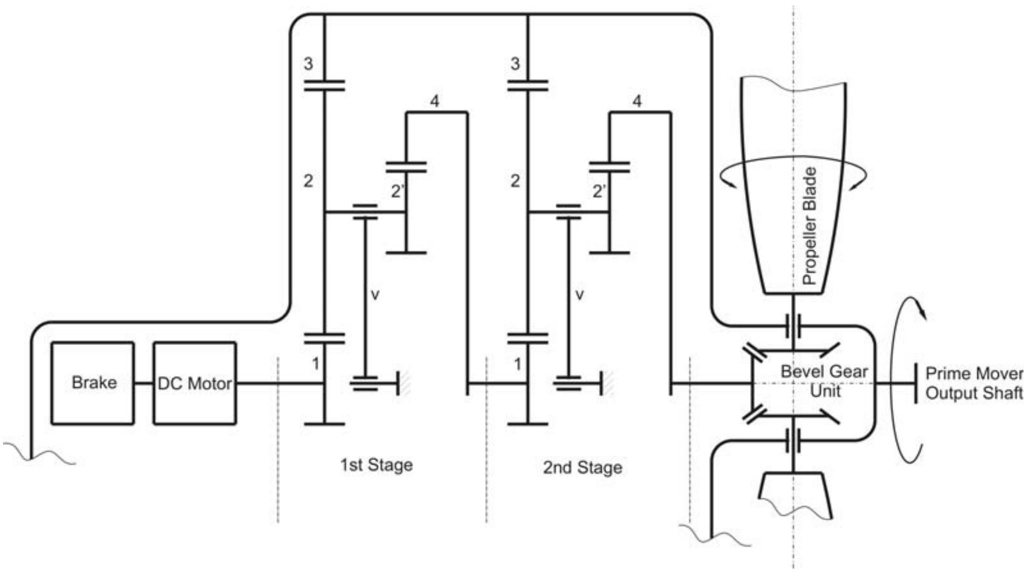

Figure 3. Schematic of an electrically actuated constant speed propeller unit.

To correct this, an electrically actuated design was developed just before World War II. Such designs are easier to manufacture and install than hydraulic systems, and the electric power is easily conveyed to the actuating motor via slip rings placed on the propeller shaft.

An electrically actuated constant speed propeller assembly consists of an electric motor with an electromagnetic brake, a two-stage Wolfrom epicyclic gear train, and a bevel gear differential unit [4], (Figure 3 and 4).

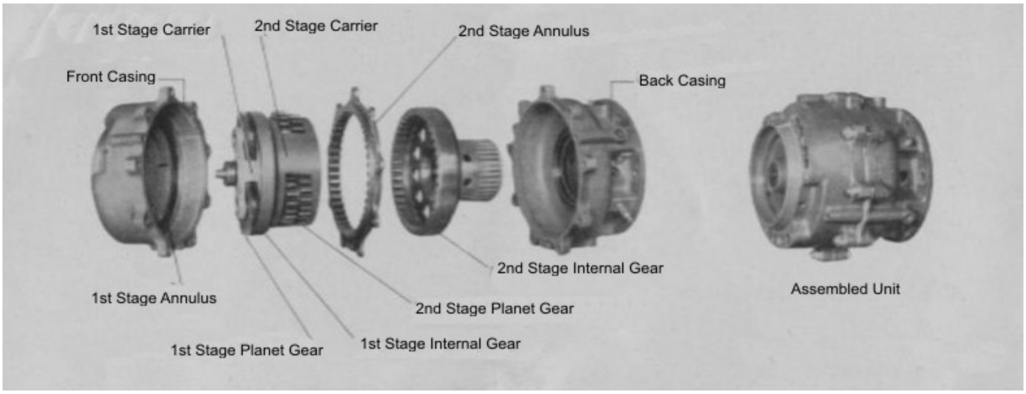

Figure 4. Breakup of a two – stage Wolfrom gear train. 1st and 2nd stage sun gears are not visible as mounted inside the respective planet carriers.

A Curtiss Electric unit can be taken as an example (Figure 5). It has a transmission ratio of i_1 = 89,18 (Table 1)in the first stage with an efficiency of 80% and i_2 = 79,20 in the second stage with an efficiency of 69%. The overall ratio of the gear train is i = 7063,2, more than adequate for accurate blade pitch regulation. The overall efficiency of the geartrain is 55%, meaning that the drive is only partially self-locking, and a brake is needed.

Table 1. Wolfrom gearset teeth numbers for a constant speed propeller unit.

First Stage	
Gear	Teeth number Z
1	12
2	54
2’	43
3	-120
4	-109
Second Stage	
Gear	Teeth number Z
1	10
2	18
2’	16
3	-46
4	-44

Although displaced by hydraulic solutions in the mid-20th century in aircraft design, the electrically powered propeller is currently making a comeback in light aircraft applications, where engines are low powered, relatively small and simple units, and the complexities and costs of hydraulics are not an option.

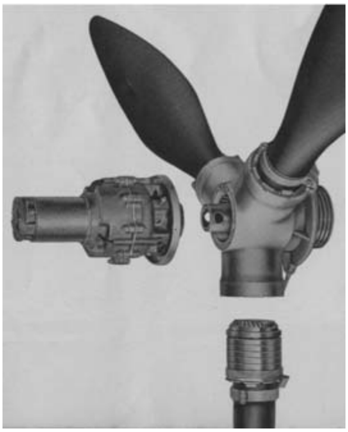

Figure 5. Assembly of propeller and pitch adjustment unit.

2.2. Small hoists

In the construction business there is usually a need to lift loads quickly from ground level to a location several floors high, and it might be not practical or economical to install a full size crane. Or a need might arise to lift smaller loads up to about 1000 kg without the assistance of the main crane on several locations at the same time.

In addition to this, the hoist must be easy to maintain and use, and draw a small current due to the temporary nature of power connections used on construction sites [5].

For example, a hoist is required to lift 200 kg at the speed of 0.5 m/s drawing the smallest possible current from the electric grid, which needs a power output of 981 W at the winding drum. In order to stay as small as possible, the winding drum will have a diameter as close as possible to that of the motor and reduction gear, let's say 180 mm.

According to these numbers, the best matched electric motor has a power output of 1100 W at 1400 min^{-1}, with a torque of 7.5 Nm, while the torque required to lift equals 177 Nm. This means that a transmission ratio of i = 23,53 is needed. According to [1], a single stage Wolfrom unit similar to that in Figure 2 is used with the ratio of i = 25. This unit operates at an efficiency of 90%, which is still suitable for continuous use. Wolfrom units are generally used for hoists up to 300 kg, and a ratio of i = 36, with an efficiency of 87%. A brake is needed as the transmissions are not self – locking.

Machines with motors in excess 1500 W operate using conventional two – stage reduction gears as a Wolfrom gearset would heat up excessively transmitting such amounts of power, resulting in lubrication problems.

Self – locking gearsets are used only in intermittent applications, such as actuating ship access ladders.

2.3. Applications in regulation

A relatively small Wolfrom unit can easily replace a compound train consisting of a large sector gear and a worm drive used to operate a butterfly valve. The drive is compact, and works well in a damp or submerged environment.

As efficiency is not an issue, and drives are used intermittently to provide 90° rotation, self – locking gearsets with ratios i = 230 or more can be used.

3 CONCLUSION

A Wolfrom planetary geartrain should be used in applications where a large reduction ratio is required, and the reduction gear must be a relatively small and lightweight design. As it is a compound planetary, a Wolfrom drive will be smaller and lighter than a conventional reduction gear, which would certainly need two stages to reach a ratio of i = 16, which is the minimum possible using a Wolfrom gearset. Larger ratios beyond i = 36 would probably need a three stage conventional gear drive, and the Wolfrom becomes a light and compact solution which carries an additional benefit of having a diameter very close to that of the drive motor, which can be an asset during assembly.

The only limiting factor to the use of Wolfrom gearsets is its operating efficiency, which is about 91% at i = 16, while a two stage conventional reduction gear would operate at 96%.

Wolfrom efficiency finally descends to about 87% for i = 36, where a conventional reduction gear would still operate at about 94-95% efficiency.

From this, it is obvious that the Wolfrom gearset is limited to small power outputs for continuous use, and the gearset is usually mated to motors up to 1500 W.

Finally, a self-locking Wolfrom unit can be used instead of a worm drive unit in regulation or intermittent use applications.

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