Planetary gear reducers - merely a question of efficiency?

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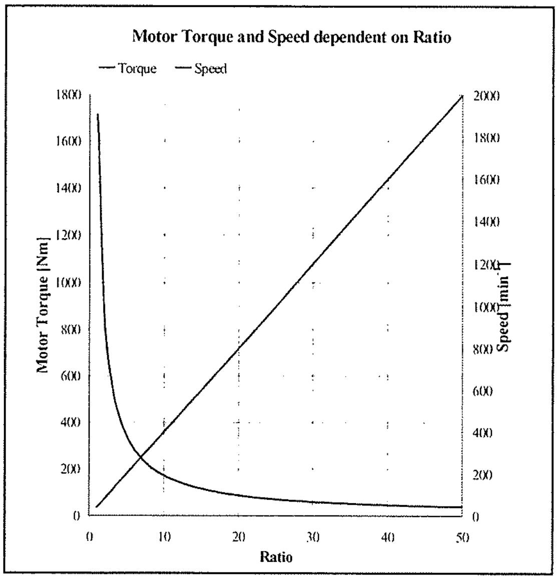
ABSTRACT

Planetary gear drive technology is wide spread in highly reliable applications from automatic car gears to space shuttle mission. However in the lift business worm gear drives traditionally have a very strong position an due to the highly competitive marketplace up to date technology usually is introduced with delay compared to other industrial fields. This now is expected to change by the requirement for compact drives in machine-roomless lifts.

In this paper a technical and commercial comparison of different drive concepts is given, with particular reference to the effects on lift design, energy consumption and control equipment.

1. GEARED OR GEARLESS

Elevator drives for rope elevators have to produce their power P = Mxω mainly via torque and not speed at the output of the traction Sheave. Depending on the travel speed or rope suspension, the output speeds vary between 50 and 150 rpm. This speed range already indicates a possible gear reducer solution. As there is no space for large drives for roomless elevators, a compact drive is required. Therefore, an attempt was made with the first roomless elevators to use drives without reducers. In order to achieve at least half the torque, these solutions employed 2:1 suspension. A further step towards reducing the torque is the use of traction sheaves with a small diameter but this is limited by the necessary traction. However, nowadays, the construction of flat elevator drives with reducers is technically feasible, offering the possibility of employing high-torque drives again. The question therefore arises - Is a drive without a reducer at all advisable in technical terms? The slide shows the effect of the reducer ratio on the reduction of the motor input torque. The drive can have smaller dimensions even at low ratios. The **optimum in relation to torque and speed** lies in the customary ratio range of 20-40. (Fig. 01)



(Fig. 01)

As far as the control behaviour is concerned, there should still be a favourable ratio of the speed and position controller used with regard to the control circuit. As a result of the ratio, the moments of inertia can be reduced by their square root. Further benefits in favour of the gear reducer solution are:

Ratio of mass moments of inertia λ

$$\lambda = \frac{J_L}{J^{MG} \times i^2}$$

λ = 1 best case

λ = 2 .. 20 in Practice

index L related to Loads

index MG related to Motor and Gear reducer

- ⇒ No rope suspension required
- ⇒ No reduction in the traction sheave diameter necessary
- ⇒- Motor encoder signal multiplied by the ratio has a high definition
- ⇒ Braking torque reduced by the ratio
- ⇒ Favourable KT factor, therefore smaller controllers required

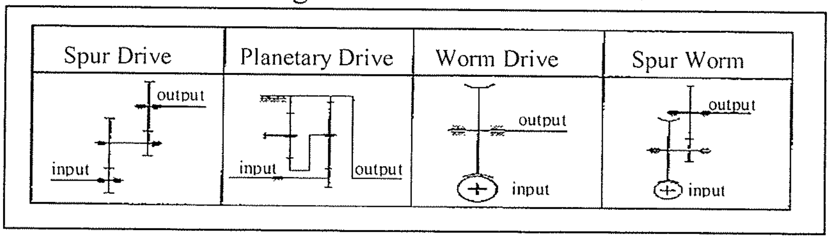
1.1 Requirements placed on a gear reducer concept

Objective: highly dynamic drives, **super-compact** especially for installation in roomless concepts, **durable**, as **maintenance-free** as possible and **energy-saving**.

Further important requirements are low vibration and low noise levels. In order to achieve these properties, the gear reducers must exhibit a low torsional backlash, have high torsional rigidity and good damping qualities. A reducer quality which lies above the usual quality range of industrial gear reducers is needed to satisfy the above requirements.

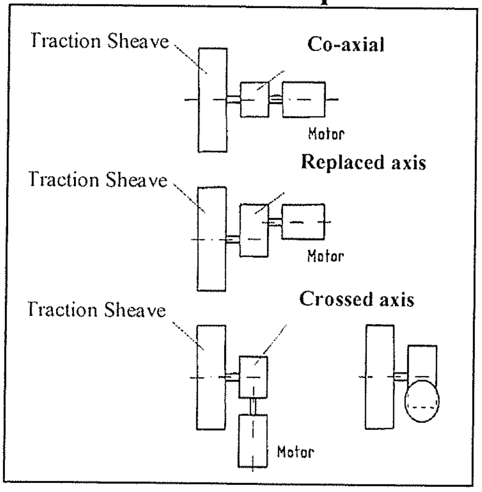
1.2 Elevator reducer concepts

The current situation as regards elevator reducers is such that spur, planetary, worm and helical worm gear reducers have to be studied. These general observations on the requirements placed on elevator gear reducers are now followed by an examination of individual gear reducer concepts (Fig.02). Other drive concepts involving reducers with a belt, cycle, eccentric or harmonic drive play a minor role and are only seldom used as they have system-related disadvantages.



(Fig. 02)

1.3 Small installation space



If the space available for the gear reducer is of major importance, e.g. for roomless elevators, worm gear reducers are to be regarded as inadequate. Spur or planetary reducers with hardened gears have smaller designs. In this connection, however, an elevator drive designer will always have to take the arrangement of the individual components into account.
Planetary gear reducers have a coaxial design, in helical gear reducers the axles are either coaxial or offset, in worm gear reducers the input and output shafts cross each other. Here, the overall concept must always be borne in mind so that the right decision can be taken.
(Fig. 03)

1.4 Ratios

The ratios used in elevators are roughly in the range of i = 10-70. Most ratios lie approximately in the middle of this range at 20-35. Depending on the functional principle of the reducers, the total ratio cannot be achieved in one stage because this is not technically feasible or an unfavourable running behaviour is produced. The gear reducers are then designed as multi-stage units. The total efficiency then depends on the efficiency of the individual stages.

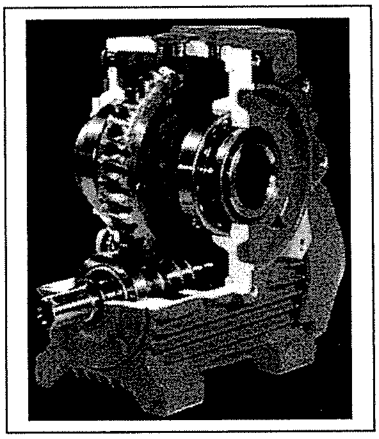
1.5 Spur gear reducers

Spur gear reducers must have two or three stages to cover the transmission ratio range demanded. A favourable ratio is in the range of 5 per stage here. Spur gear reducers have antifriction bearings and hardened gears. In order to offset the tooth meshing shock, the gears are helical. As only 1 tooth meshes per stage, the gearing must be designed with an appropriately large module, which then has a negative impact on the size. The shaft design has an equally detrimental influence on the reducer size. The forces stemming from the gearing must be absorbed with low shaft deflections. Therefore, the reducer volume achieved is not suitable for roomless elevator drives if it is to be positioned between the elevator car and the shaft wall.In the following concepts are to be examined which are currently used for roomless elevators.

1.6 Worm gear reducers

Elevator drives were previously equipped with worm gear reducers. When the high technical standard of control and brake technology were not yet available, this reducer with its self-locking property offered a certain degree of safety against uncontrolled travel motions and thus became the standard reducer for elevators. This also explains why in the past safety stops to prevent upward motion were not prescribed. These reducers were then **overdimensioned by several factors** so that no risk through wear could occur. As a result, very large elevator drives were produced which necessitated a machine room. This reducer is now also used for roomless elevators. What advantages and disadvantages this reducer concept offers for these elevators, with regard to the new demands placed on compactness and high efficiency, are to be examined in the following.

1.6.1 Design



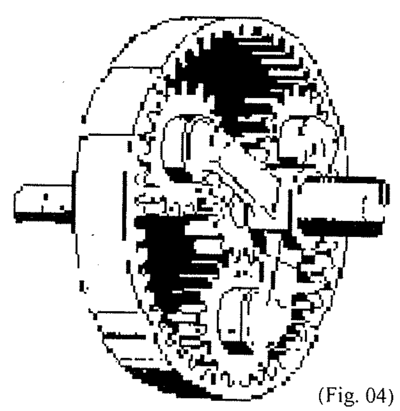
The worm gear reducer can be designed with one stage in an average transmission ratio of range around 30. As only two geared components mesh in one stage, this results in a simple and low-priced design comprising the worm gear and worm. The worm gear is made of bronze and is milled. The worm has ground teeth and one or several threads. In view of the large sliding component in the tooth mesh, the pairing of hardened steel and bronze is very important for the resistance to scoring, especially during starting when a lubrication film has not yet built up.The material bronze boosts the running-in behaviour but has the disadvantage of low strength, i.e. approx. **300 N/mm²** and therefore **three times lower** than hardened spur gears, which in turn has a negative influence on a compact design. One advantage is the high intrinsic damping through the large sliding component. Efficiency is particularly low during starting. Nowadays, more advanced worm gear reducers have **antifriction** bearings to compensate for other sliding components in bearings. The use of synthetic lubricating oils leads to an improvement but they are also employed nowadays in other high-performance reducers and so the same lubricants must be assumed in any comparison.

1.7 Spur worm gear reducers

To improve the efficiency of the worm reducer, they are made by combining a worm gear reducer and a spur gear reducer. The high-speed stage is designed as the worm stage owing to the lower flank loading. The output stage is designed as the spur stage, offering the advantage of the load-bearing capacity and the low sliding component. This results in better overall efficiency.

1.8 Planetary gear reducers

Planetary gear reducers (Fig. 04) are new to elevator technology and have only been used for elevator drives for about 10 years. Planetary reducers, however, have been time-tested in other branches and have become the standard there.Planetary gear reducers are, for example, used exclusively for **automatic transmission** in **cars** or as **speed reducers in aircraft engines**. They have been employed since the early eighties in automation technology for highly dynamic applications and have now become the **standard reducer for robots.**



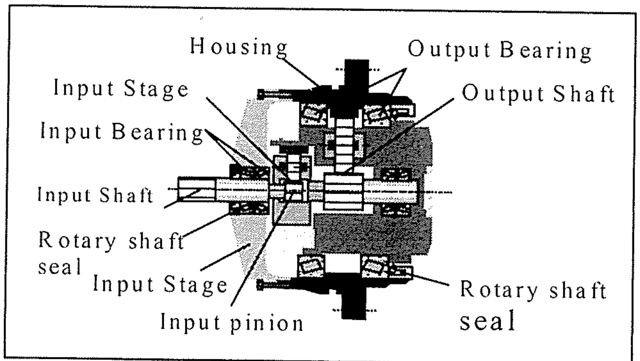
(Fig. 04)

Spur gear stages which are joined coaxially are created between the sun gear and planet gear and between the planet gear and ring gear. Planetary gear reducers can have 3 or more planet gears, therefore resulting in power splitting leads to multiple tooth meshing. In this way a super-compact reducer is possible with a view to transmitting high torques. The module can be selected appropriately smaller than in a simple helical reducer. However, ratios of only 3 to 10 are feasible within one stage. Thus, planetary reducers in the elevator sector also have two stages with ratios of i=30

1.8.1 Planetary gear reducers from alpha

The alpha planetary elevator reducer has a special arrangement of the two planetary stages with a view to achieving compactness; as a result the installation length is again shortened (Fig.05).

The fact that the ring gear of the input stage is connected to the planet carrier of the output stage leads to a reduced ratio according to the formula shown here .



(Fig. 05)

$$I_{total} = (i_1 \times i_2) - (i_1 - 1)$$

Example:

$i_{total} = (10 \times 10) - (10 - 1)$

$i_{total} = 91$

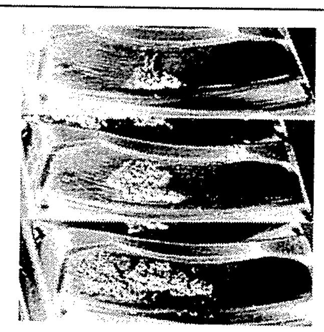
After this analysis, the technical data of the reducer concepts used most for roomless elevators are now to be compared and examined for their suitability in terms of maintenance-free, durability and energy-saving properties. Compact dimensions are taken for granted.

2. DURABILITY

Very high demands are placed on the service lives of elevator reducers. At 20,000 hours of operation, their service life is **ten times** longer than that of car gearboxes. A long service life is only achieved through **minimum wear.**

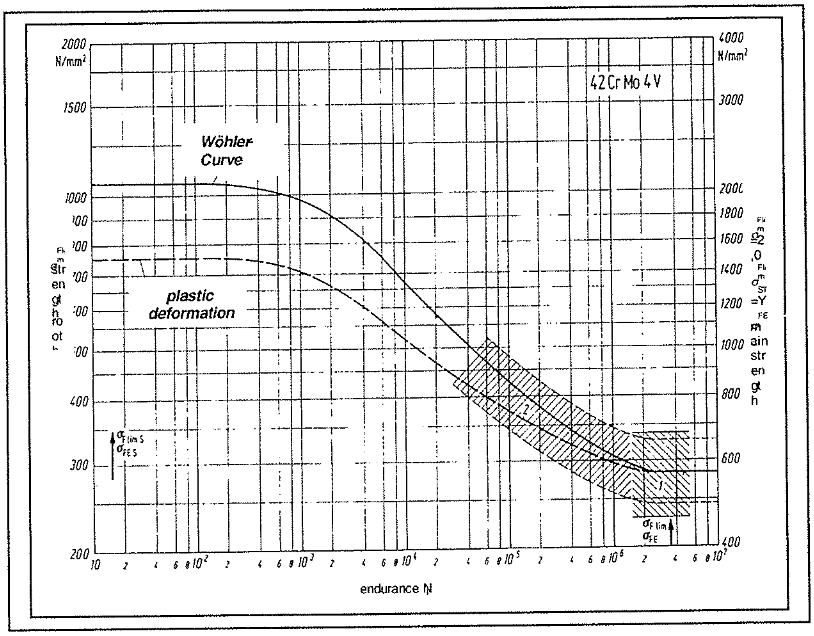
2.1 Wear analysis

In a worm gear reducer with a large sliding component the worm gear in particular has to be checked for wear owing to the softer material. Wear on a tooth flank starts when the admissible contact pressure (Hertsche contact stress) is exceeded. In the first stage plastic deformation occurs, irregularities are smoothened. Depending on the sliding velocity and number of load cycles, however, material becomes detached if the contact pressure is constantly exceeded. This is so-called pitting. (Fig.06) shows the course of damage on a worm after pitting has started. After material has become detached, the bearing



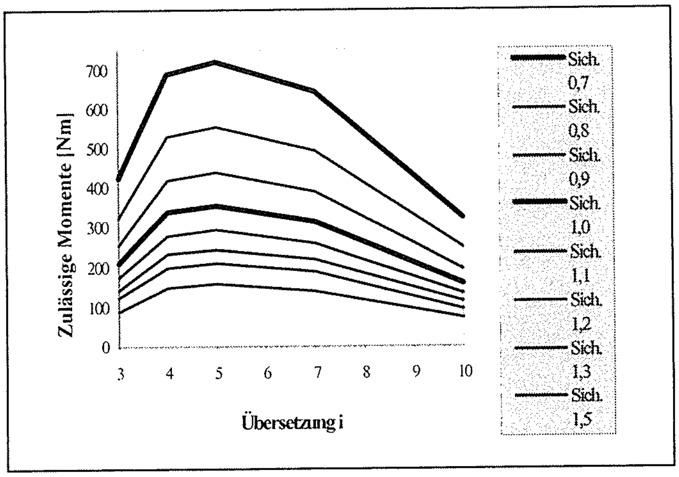
(Fig. 06)

component becomes increasingly unfavourable and pitting propagates until the tooth ruptures. Pitting is also related to the sliding velocity. Therefore, high contact pressures on the tooth flanks and high sliding velocities are to be avoided in a worm gear reducer. The **planetary gear** reducer has practically **only rolling** components in the tooth mesh along the line of action. The tooth flanks are **hardened** and therefore have a three times achieved and thus a considerably higher power conversion with the same volume.



(Fig. 07)

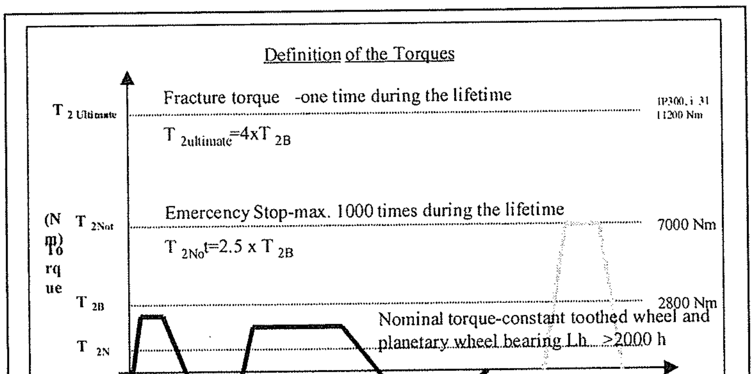
If a reducer is to be designed to have an infinite fatigue strength, its gear teeth have to be rated to the Wöhler characteristic. (Fig. 07). This shows the characteristic for the material of the gearing components. If the flank contact pressure in a planetary reducer is designed so that the characteristic is not exceeded for the load cycles, the reducer has infinite fatigue strength and is not subject to wear from pitting. Here, safety values can be laid down depending on the ratio (Fig.08).



(Fig.08)

2.2 Fracture Torque

The maximum admissible values up to 1.5 can be obtained at a ratio of i = 5 within one stage. **2,5 times** the torque is still admissible as an emergency-off torque. (Fig. 09) shows the definition of the torques again. Even a torque **4 times** higher than the maximum torque is possible during acceleration before tooth rupture.

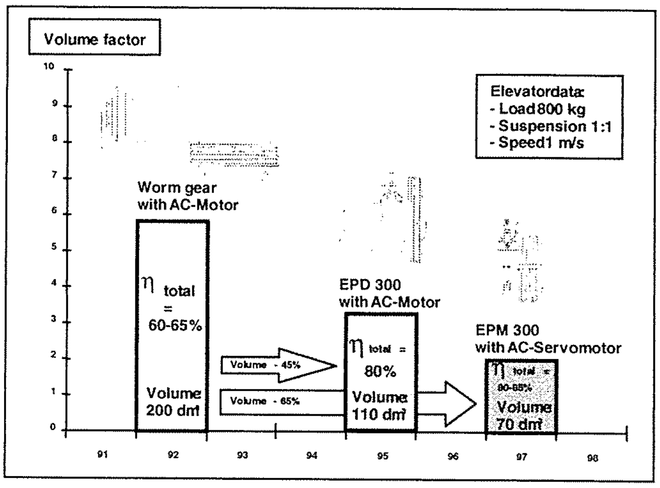


(Fig. 09)

3. ADVANTAGES

3.1 Size comparison

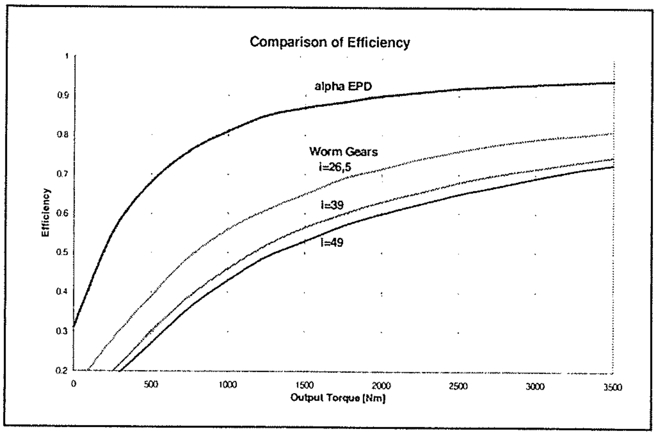
The advantages in reducer design outlined thus produce a considerably lower volume with the same performance data. (Fig. 10) It shows the reduction in volume when a planetary gear reducer is used and a further reduction thanks to the combination of a planetary reducer and synchronous motor.



(Fig. 10)

3.2 Efficiency

Nowadays, elevator reducers must also have an ecologically sensible concept as they make a large contribution towards energy consumption, above all in conurbations. Efficiency is the crucial factor for an **energy-saving drive**. If the two reducer concepts which can be considered for a roomless drive are now compared, this produces the following features:



(Fig. 11)

3.3 Starting behaviour

Every reducer exhibits different efficiencies over the effective speed range. Stiction stemming from the gears, the bearings and the sealing elements has to be overcome, especially in the starting phase.In elevators the starting torque is up to double the operating torque at constant travel. The forces on the tooth flanks also rise proportionally. If in one gear stage the sliding component is high and if mainly rolling does not commence immediately, this sliding can only be improved when a hydrostatic lubricating film has built up and the stiction is overcome. In a worm gear reducer these efficiencies are **less than 50%** in spite of the antifriction bearings and synthetic polyglycols in the lubricant. The lower the ratio is, the worse this value becomes. Planetary reducers have almost no sliding component in the tooth mesh and therefore hardly any differences in the starting and operating efficiencies. The advantages of this are:

⇒ *The drive can be dimensioned accordingly smaller.*

⇒ *The mains required can be rated for a lower starting current.*

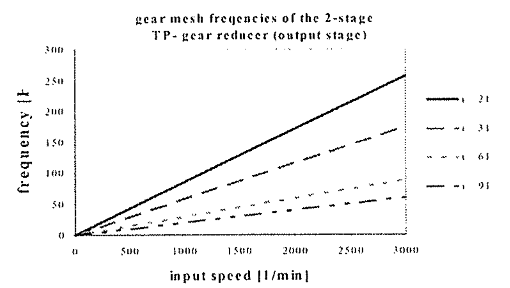
⇒ *The controller concept does not need to compensate for the starting shock with complicated equipment.*

During operation efficiencies of over 80% can be attained with worm gear reducers, depending on the ratio and loading (Fig. 11) but, owing to the system-related sliding component, these efficiencies cannot be compared with those of planetary reducers where they are as high as **95%** even with 2 gear stages.

If the effect of the efficiencies is now compared in various designs, this produces the following relationship.

3.4 Quiet running

Noise levels and vibrations determine the quality of smooth running in a gear reducer. The crucial factor for vibrations and noises is how the gears mesh and what frequencies occur. In spur gearing, such as also exists in a planetary gear reducer, an attempt is made, when very smooth running is demanded, to offset the tooth mesh shock by increasing the contact ratio in the tooth mesh with helical gearing. The tooth mesh frequency in a gear reducer is proportional to the input speed; in a planetary gear reducer there is the following relationship for the output stage: (Fig. 11) e.g. i=31, n=1500 rpm, fz = 0.0581x1500 = 87.15 Hz With a worm the meshing frequency is f = gxn/60. For G = 3 stages, n = 1500 rpm = 75Hz. There is therefore no appreciable difference in the systems as regards the vibration behaviour for the load-dependent stage.



i = 21 Þ fz= 0,0857 x n_1
i = 31 Þ fz= 0,0581 x n_1
i = 61 Þ fz= 0,0295 x n_1
i = 91 Þ fz= 0,01978 x n_1

F_z=gear mesh frequency (Hz)
n_1= input speed (rpm)
i= ratio of the gear reducer

(Fig. 11)

Owing to the large sliding friction component the worm reducer exhibits high intrinsic damping. The important aspect is that other systems are not caused to vibrate due **to resonant frequencies**. For the planetary reducer the resonant frequency is calculated using the following formula. This indicates the connection between the moments of inertia of the reducer ratio and the torsional rigidity. When correctly designed, the resonant frequencies of the drive therefore lie outside the usual resonances of the elevator installation owing to the high torsional rigidity of a planetary reducer.

$$f_{R1} = \frac{1}{2 \cdot \pi} \cdot \sqrt{C_{t21} \cdot \frac{J_L + J_{MG} \cdot i^2}{J_L \cdot J_{MG}}}$$

f_{R1}: resonant frequency on the input side (1/s=1Hz)

C_{t21}: torsional rigidity of the gear reducer (Nm/rad)

conversion in Nm/rad: 1 Nm/arcmin=1x60x180 rad

J_L: mass moment of inertia of the load (kgm2)

J_{MG}: mass moment of inertia of the motor and gear Reducer on the input side (kgm2)

i: ratio

3.5 Noise emission

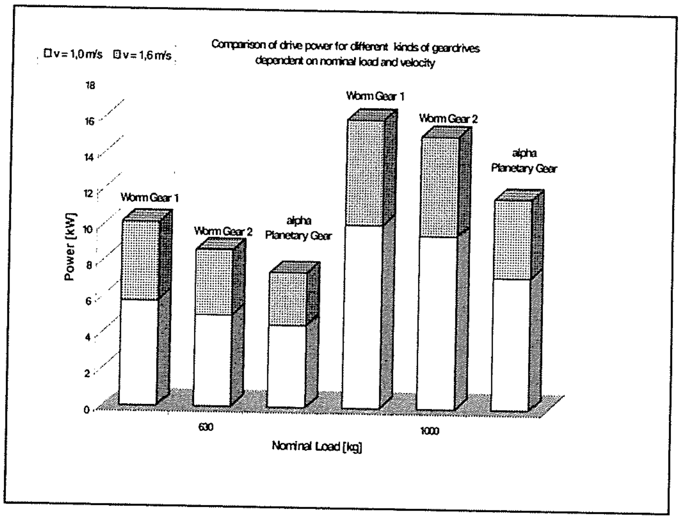
A low noise level must be observed, especially with roomless elevator drives where the drive is positioned directly in the shaft. The noise level is often left to a subjective assessment and depends on several factors at the same time. One quantifiable factor is the sound pressure measured in dB(A).In the table provided various gear reducers with the same power rating and input speed are measured. Here, there is a better value for the worm reducer owing to the system. However, with the planetary gear reducer the same values as the worm reducer can be achieved depending on the quality standard. Tabular summary of the advantages and disadvantages to provide a clear overview.

Spur Drive (2-stage)	**Planetary Drive** (2-stage)	**Worm Drive** (1-stage)	**Spur Worm Drive** (2-stage)
67 dB (A)	62 dB (A)	59 dB (A)	59 dB (A)

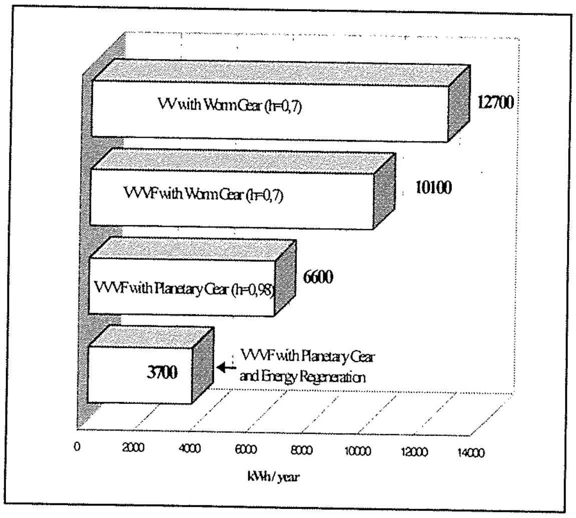
4. SAVING OF ENERGY

In a comparison of the different Drive Concepts, Planetary Drives and Worm Drives in a Testing Application, there will be find out the result (Fig. 13). Recognizable here is the low termination of the Planetary Drive, this is current in dependence on the travel speed as well as on the nominal load.

Observing the Saving of Energy Factor of such systems, there is to see the following. (Fig.14)



(Fig. 13)



(Fig. 14)

SUMMARY

As already mentioned at the outset, a reducer concept is in general the correct solution for elevators with a travel speed **of less than 3 m/s.** If the reducer is to be very space-saving, maintenance-free, durable and energy-saving, a **planetary gear reducer** is the best concept in this case. In conjunction with modern synchronous motor technology, total efficiencies of over 90% can be attained. Roomless elevators offer advantages in the building design and, as rope elevators, do not need any environmentally harmful transmission media, such as hydraulic oil. Planetary gear reducers with a synchronous motor are the right drive concept for such elevator installations.

5. COMPARISON PLANETARY GEAR – WORM GEAR

characteristics	Planetary gear reducer	⇨	worm gear	⇨
⇒ **Fracture Torque**	• 3x3,5=10,5 gear pairs sun wheel, planet • 3x3,8=11,4 gear pairs hollow wheel, planet in meshing	• High safety-against fracture of gear	• 3-5 teeth	• teeth must be dimensioned very big

characteristics	Planetary gear reducer	⇨	worm gear	⇨
⇒ **Nominal torque**	• Performance is based on three gear meshes: Sun wheel/pinion, planet, hollow wheel	• Compact design optimum use of the toothed wheel work symmetry: all forces neutralize each other	• One gear meshing	• 80-90% of the worm wheel not in meshing-> outward bending of the worm
⇒ **Wear**	• Optimum geometry when started	• No running-in necessary	• Optimum geometry after running-in	• Wear, increase of backlash
	• Rolling off gear meshing		• In gliding movement in meshing increase of pittings must be accepted	• Wear, increase of Backlash
	• No pittings possible	• No increase of backlash		• Wear, increase of Backlash
		• Constant high travel comfort, during the whole life-time		• Permanently worsening of the travel comfort
⇒ **Starting torque**	• Starting torque =running torque	• Smooth acceleration	• Starting torque 4x higher than running torque	• Starting jolt
⇒ **Efficiency**	• > 93% (nominal) • > 93% (start)	• Low start currents possible	• 60-80% (nominal) • 20-40% (start)	• energy consumption • heating up •with reversal torque: danger of tooth fracture, wear
	• forward efficiency =reverse efficiency		• reverse eff. only 50 % of forward eff.	
⇒ **Lubrication**	• Low oil volume	• Low oil costs	• extensive	• High oil costs
	• free mounting position	• any mounting positions	• dependent mounting position	• only one mounting position
⇒ **Noise**	• quite in a good quality of the gear	• Smooth running	• quite	•smooth running

Sources:
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