Compact, Lightweight Valve Actuators with Polymer Gears Using the Harmonic Principle

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Abstract

Traditional electromechanical actuators for fluidic systems (hydraulics, pneumatics, processing technology) use (metallic) spur and planetary gears. The multitude of components of those gears have a negative impact on space, accuracy and cost. Harmonic Drive steel gears have long been known for their precision and power density, also in valve acutators. By employing a flexible gear element, the Flexspline, high precision and high reduction ratios can be achieved in a small envelope with few components and low weight.

Transferring the gear principle into moulded plastics makes it possible to use its advantages also for large series, integrating additional functions in cost-efficient, lightweight components with tight tolerances. Fluidic applications include thermostatic valveheads, but also pumps for very small liquid volumes as in medical devices.

This paper presents the principle, application examples and some research results on improving gear efficiency and durability by varying materials and design.

KEYWORDS: gears, valve actuators, thermoplastics

1. Introduction and functional principle

A strain wave gearing only consists of three components: the elliptical Wave Generator (WG), a flexible, outwardly geared element, the Flexspline (FS) and an internal ring gear, the Circular Spline (CS). The WG elliptically deforms the FS. The teeth of the FS engage with the teeth on the CS across the major axis of the ellipse.

As soon as the WG starts to rotate (e.g.) clockwise, the zone of tooth engagement travels with the major elliptical axis. Because the FS has two teeth less than the CS, each turn of the WG moves the FS two teeth (in this case anti-clockwise) relative to the CS. Thus, very high reduction ratios are accomplished within a single gear stage.

The most known version is a WG which employs a thin-race bearing (shown in **Figure 1** left), the outer ring of which is constantly being deflected with the rotation of the WG. For applications demanding less precision and durability, the deformation of the FS can be achieved by two rollers spaced apart on a carrier. Polymer gears are often used in small devices where the necessary power is generated by a high-speed, low-torque motor for economic and weight reasons. Using a FS with internal teeth in addition to the external ones and designing the WG as an integrated planetary prestage yields extremely high reduction ratios of up to 1000:1 while not generating any additional volume and thus enables designing extremely compact precision actuators.

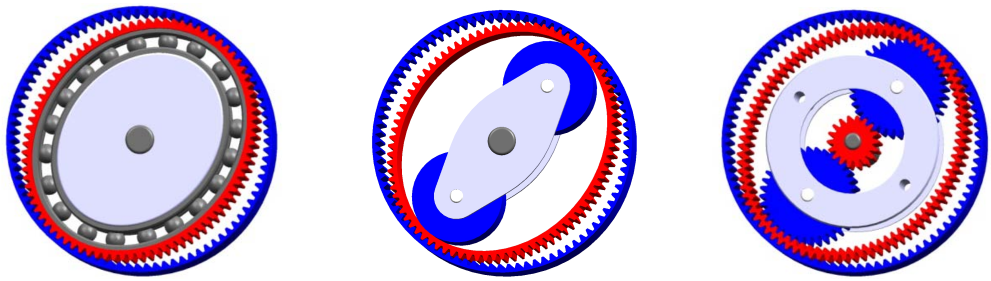

Figure 1: Different embodiments of the Wave Generator:
thin-race bearing (left), two rollers (centre), planetary prestage (right)

Various geometries of the FS make it possible to adapt the gear configuration to requirements of the specific application, like for very flat spaces or with an outward flange for large hollow shaft diameters.

The properties of thermoplastics make it possible to realise extremely lightweight gearheads and actuators influencing the concept of the overall system and paving the way for more compact solutions. This in turn reduces total energy consumption and leads to improved dynamics. A Harmonic Drive Polymer gear with a ratcheting torque of 22 Nm e.g. weighs 69g and thus has a torque density of 319 Nm/kg.

So far, Harmonic Drive Polymer systems have been developt ranging in size from an outer diameter of 10mm to 68mm and with reduction ratios between 20 and 4000. Two examples are shown in **Figure 2**.

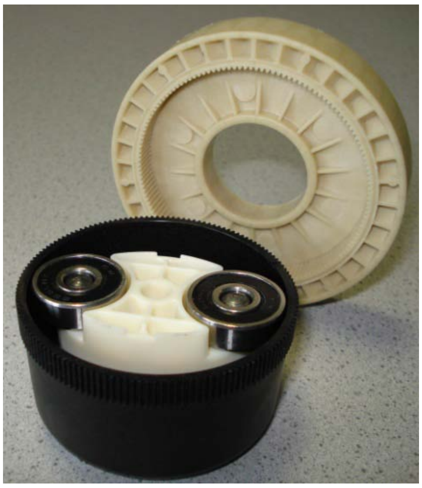

Figure 2: Standard Harmonic Drive Polymer gear component sets

A key advantage of thermoplastics is their processability by injection moulding. This makes it possible to economically manufacture large quantities of components with excellent dimensional repeatability and surface properties. After a one-time investment in high-end moulding tools, complex shapes and functions like fastening aids or safety clutches can be integrated into components and thus facilitate assembly and reduce serial costs. Of course this in return means that

Using high-temperature thermoplastics, e.g. PPS or PEEK makes it possible to specify Harmonic Drive Polymers Actuators for temperature ranges that have been necessitating the use of metals. Continuous operation at 150°C is a development target.

2. Applications in fluidic technology

In fluidic applications, there are several fields of use for Harmonic Drive Polymer actuators. One is drives for highly accurate valves for steam or water, e.g. for thermostatic control of flow rates.

For one battery driven application requiring 100N of linear force at very low speeds in limited space and with excellent efficiency, a novel linear drive was developed.

Conventional linear actuators use a multitude of spur gears to increase the motor torque and a spindle/screw as means to transfer the gear train's rotational energy into a linear motion. Self-locking is achieved by the low efficiency of the spindle. The spur gears require a significant amount of design space. The spindle provides a high reduction ratio in itself, so the spur gear stages will be designed to achieve a medium reduction ratio.

In the novel drive a Harmonic Drive with a very high reduction ratio is employed as the primary stage driving a pinion at a very low speed. This in turn drives a rack – with excellent efficiency. In order to reduce the load on the pinion, there are several pinions and gearings on the rack distributed around its circumference. The self-locking necessary in the specific application is achieved by appropriate design of the high-reduction Harmonic Drive stage.

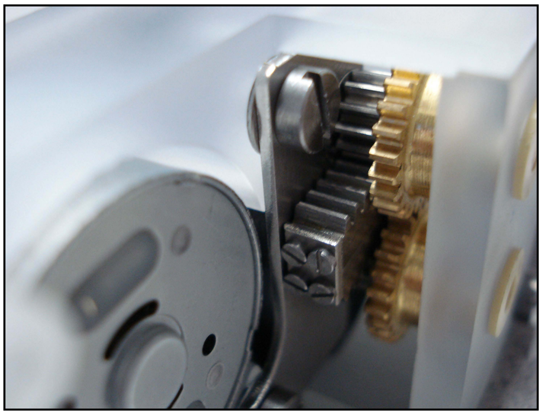

Figure 3: Mock-up of novel linear drive

Initial tests performed on mock-up actuators with non-optimised first stage (strain wave) polymer gear components and off-the-shelf (steel) rack-and pinion components yielded an efficiency very close to the serial solution (current consumption, **Figure 4**). Depending on direction and sample, current varied between 16 and 28 mA in comparison to the serial gear's 20 mA. Application- and load-specific optimization of the gear will drastically improve efficiency which is highly dependent on the usage factor (relation between applied load and maximum permissible load) of the gear.

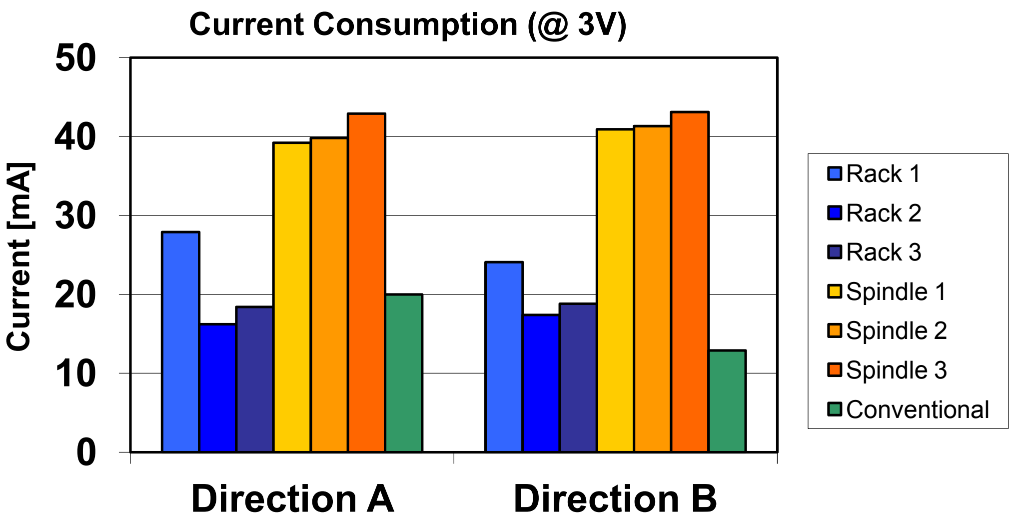

Figure 4: Current consumption of novel linear drive vs. serial solution

As can also be seen in Figure 4, using a Harmonic Drive Polymer gear together with a spindle led to higher than acceptable current consumption. This is due to the fact that two self-locking (i.e. low-efficiency) systems are combined.

Increasing the accuracy with which ball cock valves are being controlled is another field of application for the systems. Because of the gear principle, there is zero backlash as opposed to spur gear actuators. Using this feature together with the inherently high backdriving torque of strain wave gears greatly improves controllability of the valve. Actuator size and weight, although not of primary interest in this application, can also be optimized.

Harmonic Drive Polymer systems can also be used to create pressure in distribution systems for fluids such as centralised lubrication systems or even pumps for infusion of liquid pharmaceuticals and other agents. Against conventional gear trains, precision of throughput can be increased. Designing drug delivery systems for disposal after a certain period of use rather than for sterilization and re-use gives several advantages:

- For the operator, cleaning procedures and associated liability risks are obsolete
- Materials need no longer be able to continuously withstand high temperatures and/or radiation employed in sterilization processes. An initial sterilization is sufficient.
- Durability requirements can be lowered and thus systems designed smaller and more cost-efficient.
- In many cases, lubrication can be eliminated which in turn facilitates construction as sealing becomes much simpler.

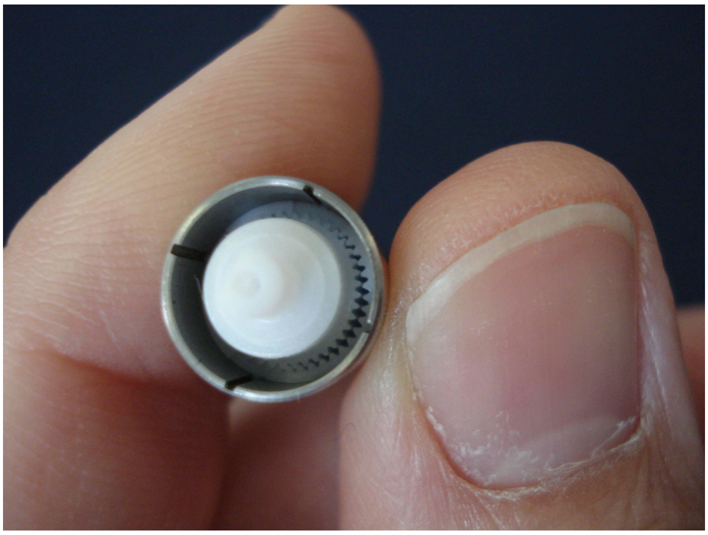

Figure 5: Miniature Harmonic Drive Polymer Gear

Micro injection moulding and assembly techniques make it possible to produce micro actuators as shown in **Figure 5**. Prototype gears have been manufactured by a specifically developed moulding and finishing process.

3. Torque and efficiency improvements

Intensive research has been carried out on a gear with the following characteristics:

- Gear diametre 21mm
- Outer diametre 26mm
- Reduction ratio 400:1
- Weight 4g

During the course of develeopment, main improvement areas against the initial design were increase of torque capability, efficiency and durability.

Torque carrying capacity of the gear was significantly improved by modifying tooth shape (see **Figure 6**). The torque loss caused by using a less rigid FS (for efficiency reasons) could be compensated by modifying WG kinematics. Additional improvement was achieved by using ball bearings and/or modified friction bearings.

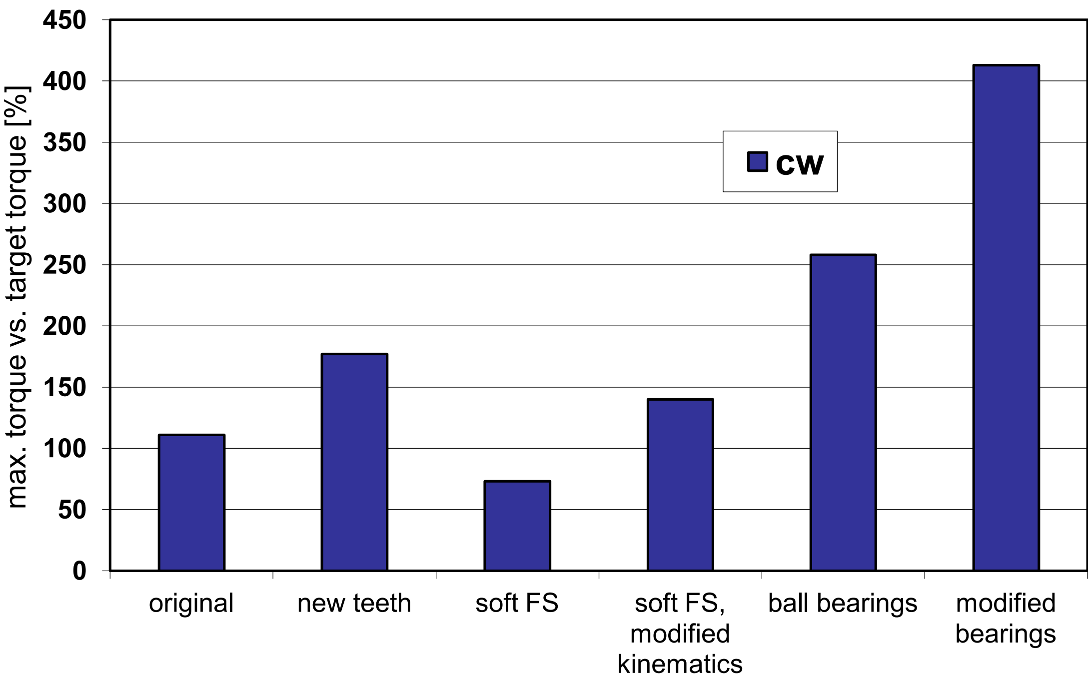

Figure 6: Torque carrying capability

Similar improvement measures were taken concerning efficiency of the gears. As can be seen from **Figure 7**, material, bearings and lubrication have significant influence on the results. As expected, using a less rigid FS caused a dramatic increase in efficiency.

However also the effect of various bearing types and lubrication variation can clearly be seen.

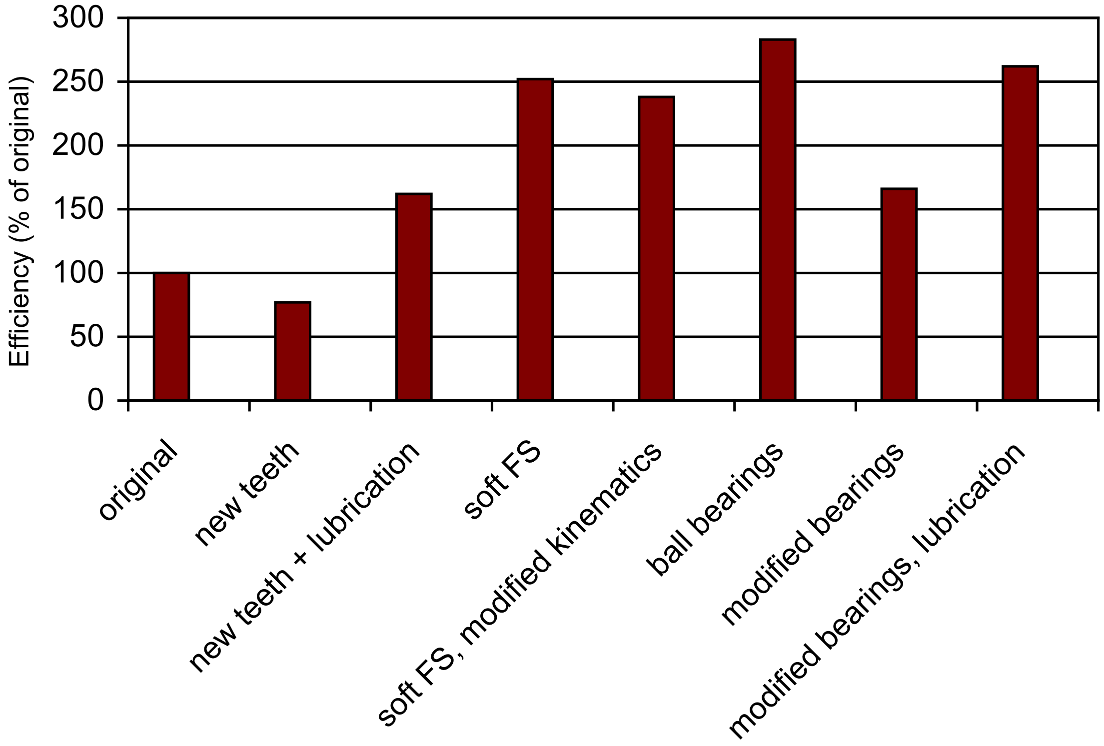

Figure 7: Efficiency

After achieving satisfactory torque and efficiency values, durability was improved. Apart from some materials that could not withstand the number of bending cycles under load that were required by the applications, analysis showed wear in the teeth as the main failure mode.

Modifying the tooth shape of the CS with simultaneous adaptation of the gear kinematics drastically raised durability by eliminating wear (shown in **Figure 8**) in some critical areas. The target value could be achieved even under increased severity of the test conditions. Research on this topic is still ongoing, specially concerning material variations and FS geometry.

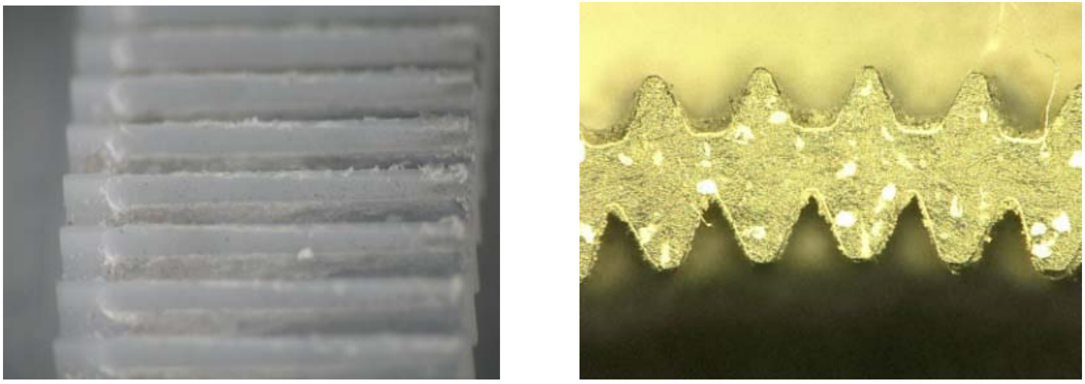

Figure 8: Wear patterns on flexsplines

In general, durability of Harmonic Drive Polymer gears is influenced by various WG types as well as by material choice and tooth geometry.

4. Material considerations for special requirements

A key factor determining durability and thus usability of plastics in a Harmonic Drive Polymer gear is fatigue resistance if employed for the FS. In addition, friction and wear properties are important. On the other hand, the stiffness of the CS determines transmissible torque and its accuracy has a big influence on both maximum torque and efficiency.

Thermoplastics usually employed for gear applications are limited in the temperature range they can be used in. Polyacetal (POM) e.g. is generally only used up to a maximum of 100°C, often lower. Even then, its stiffness is far below that at room temperature. Using a glass fibre reinforced thermoplastic material for enhanced stiffness compromises tribological properties. Most materials suitable for higher temperatures might be used for the (stiff) CS, but usually are quite brittle, thus not usable for the Flexspline. One material combining tribological properties and fatigue resistance is PEEK available from various suppliers. It requires specific adaptation of the Flexspline Geometry.

5. Conclusion and outlook

Harmonic Drive Polymer gears and actuators offer the possibility to design compact precision actuators, especially for limited durability requirements under stringent cost conditions. A novel linear actuator was developed showing the potential for improved efficiency over conventional solutions. Torque capability, durability and efficiency could be remarkably improved during research and development work. Special materials make it possible to use the systems in elevated environmental requirements. Future work will focus on further expanding the range of applicability.

6. References

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