MAGNETIC GEARING AND A UNIVERSAL JOINT – TWO FUNCTIONS COMBINED WITHIN ONE GEAR UNIT

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ABSTRACT

Strong, powerful and robust actuators suited for the harsh environmental conditions in space are needed for future missions. Electrical drives combined with magnetic gearing seem to be one of the most promising concepts. Additional functionality in magnetic wobbling gears can be gained by changing the actual working principle. By minimizing the number of functional gear stages, one additional torque transducing element has to be added. This element enables an angular displacement of the coaxial aligned input–output axis. In an extreme mode the output axis can be inclined in the opposite direction. This mode, in which gearing is no longer function, can be used for folding large structures during storage, transport, launching or shuttle.

1. INTRODUCTION

The need for space mechanisms to work their entire lifetime without needing servicing may benefit from the presence of powerful magnetic gearing technology. Conventional gearing technology needs some sort of lubrication between all force transducing elements, namely, the various teeth of the geared wheels. However, magnetic gearing technology, in which there is no contact between the force transducing elements, overcomes the problem of lubrication. This will result in a significantly improved lifetime.

However, other characteristics, especially in space applications, must be met in addition to solving the lubrication problem.

- Maximum torque density of the whole actuator is necessary for total weight reduction.
- Improved torsional stiffness of the whole actuator is expected.
- Unpowered holding torque is expected.

Additional benefits of magnetic gearing technology are due to the following:

- improved functionality and combination of more than one function in a gear stage;
- reduced complexity;
- hollow shaft;
- improved tolerance to the block-shaft condition; and
- efficiency.

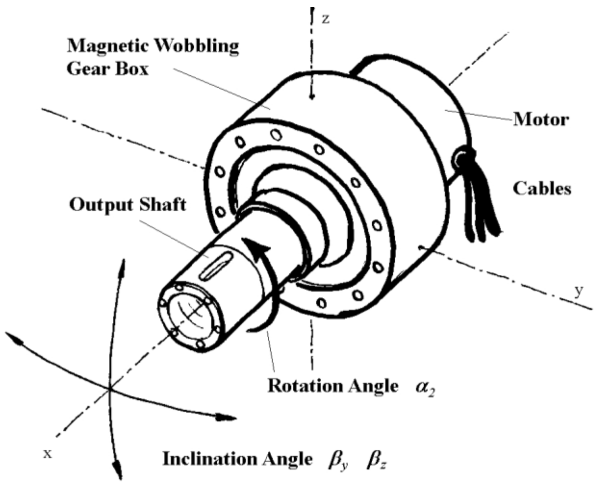

Figure 1. Magnetic Gearing Actuator with Coaxially Aligned Output Shaft, Mode 1.

2. FUNCTIONAL DESIGN

In [1] a two-stage magnetic wobbling gear is described. The so-called 'fully magnetic' gear consists of three magnetic gear wheels. The first stage is responsible for generating the gear reduction ratio, and the second stage of the magnetic gear will do the 'dewobbling' action, which is strictly necessary for operation in wobbling gearboxes.
When the number of magnetic gear wheels is reduced by one, a one-stage magnetic gear consisting of two single magnetic gear wheels will result. In that special case, the 'dewobbling' action has to be generated by an additional angular joint mechanism. Two types of universal joints are candidates for this special action:

- universal joints with crosspiece (cardan) and
- constant velocity joints (homokinetic).

Using these types of joints in a one-stage magnetic gear, additional functionality can be achieved. A coaxial shaft alignment of the input and output shafts (Fig. 1) is no longer necessary. Instead, the output shaft can be inclined in all directions up to a certain angle (β_y and β_z) without needing additional parts. Figure 2 shows such an actuator with the corresponding working range of the output shaft.

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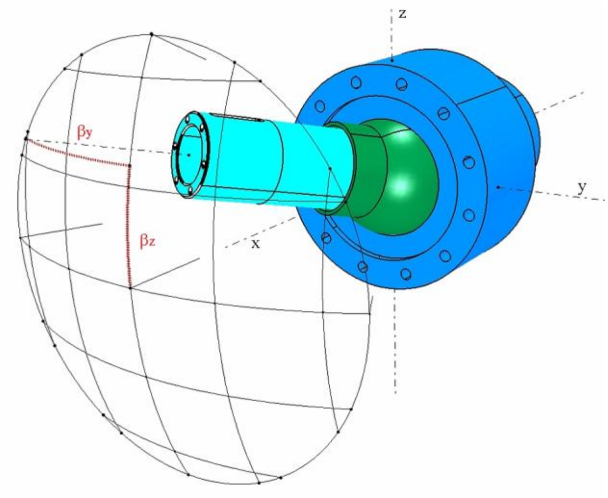

Figure 2. Magnetic Gearing Actuator with Angular Displacement of the Output Shaft, Mode 2.

These two additional degrees of motion are gained through an inherent property of the gearing mechanism. Moreover, it is possible to displace the output shaft up to 180° in a specified and no-functional gearing mode with cardan joint 'dewobbling' operation.

3. UNIVERSAL JOINTS AND THEIR CONSTRAINTS

Using a cardan joint (Fig. 4), the well-known nonlinear characteristic of the input–output transfer function (Fig. 3) has to be taken into account.

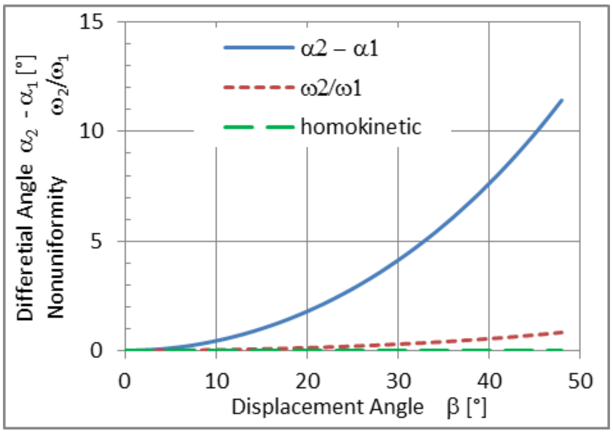

Figure 3. Differential Angle of Universal Joints.

Angular displacement angles β affect the output non-uniformity by a given amount (blue solid line). Motion (red dashed line), as well as output torque, is thereby affected. The total displacement angle acting on the cardan joint is composed of the following:

- the fixed wobble angle β_M generated within the magnetic gear and
- a variable angle β_S of the deflected output shaft.

In magnetic wobbling gears, the value of the wobbling angle β_M is about 5°. Therefore, the contribution of cardan joint influence to motion non-uniformity is very small. Depending on the special needs of an actuator and the corresponding application, this influence can be neglected or easily compensated by means of linearization.

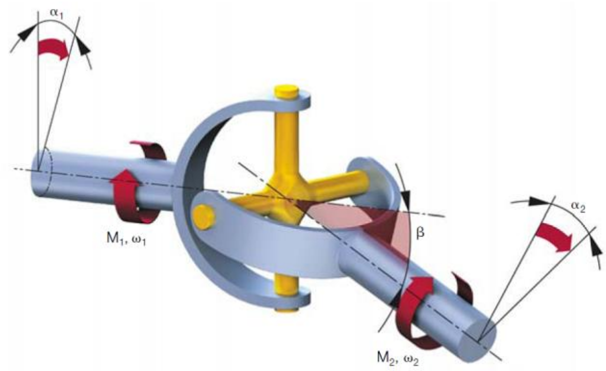

Figure 4. Universal Joint with Crosspiece [4].

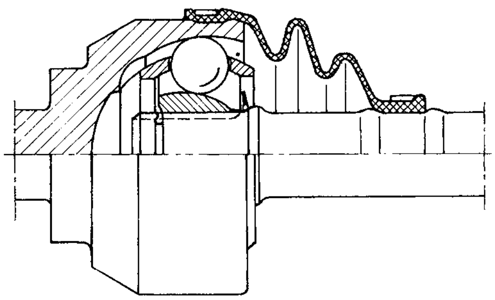

Figure 5. Homokinetic Universal Joint [3].

In the case of using homokinetic joints (Fig. 5), linear behaviour and smooth operating conditions are guaranteed. The corresponding characteristic is shown as a green dashed line (Fig. 3).

From the perspective of lubrication, both cases have to be considered. In both cases, we have to deal with pure rolling at all joint connection points, which are constantly touching. State-of-the-art solutions for universal joints with a crosspiece (cardan) utilize needle bearings. Homokinetic joints are commonly used in front axle shafts. Conventional balls are used as force transducing elements.

4. TORSIONAL STIFFNESS

The use of magnetic forces in a gearbox is accompanied by elasticity, in particular, by torsional elasticity. The proposed design consists of one pair of magnetic gear wheels interacting simultaneously in a gearing mode and in a clutch mode. The elasticity depends on the specified degree of torque-transferring capability as well as on speed-reducing capability.

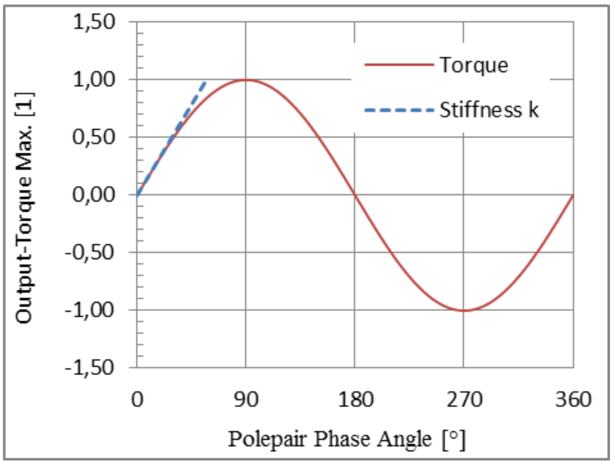

Figure 6. Estimation of Torsional Stiffness k.

This elastic behaviour has of sinusoidal shape. As seen in Fig. 6, the maximum output torque is reached at an output shaft rotation angel of

$$\alpha_2 = \frac{360°}{N} \cdot \frac{1}{4} \quad [°] \tag{1}$$

where N is the reduction ratio. If the external torque exceeds the maximal output torque Mmax, the output shaft will lose magnetic contact and will slip into the next stable magnetic position. Maximum stiffness is observed at an output shaft rotation angle α_2= 0°. To estimate the torsional stiffness value, we have to refer to Eq. 2.

$$k = M_{\max} \cdot N \quad [Nm/rad] \tag{2}$$

Eq. 2 describes the simple relationship between the torsional stiffness k, the maximum output torque $M_{\max}$ and the reduction ratio N in a magnetic wobbling gear with one magnetic wheel pair.
In fact, the elasticity is significantly less compared to 'fully magnetic' gears because one complete pair of magnetic gear wheels is absent.

5. TORQUE DENSITY

The torque density will also improve significantly. Some limitations dominating the design of 'fully magnetic' gears drop off at single-stage magnetic gears. These limitations are the following:

- same wobbling angle for all magnetic wheels;
- no overlapping between the magnetic wheels;
- near 100% usage of the magnetic area of the wobbling wheel;
- magnetic 'dewobbling' gear stage acting solely as magnetic coupling device;
- wobbling wheel has to act in both magnetic gear stages; and
- limited axial length of the entire magnetic setup.

Neglecting these limitations, the area of magnetic overlapping between the two gear wheels now can be chosen more easily. The magnetic system can be placed in an optimized region. Axial placement, wobbling angle and active magnetic circuits are design parameters, which are optimized independently. As reported in [1], an increase in torque density of a factor of 1.4 has been calculated. This result was achieved under the limitations described above.
The new 'freedom' in designing and optimizing wobbling magnetic gearing systems shows some significant improvements in torque density. Compared to 'fully magnetic' systems, the torque density can be increased by a factor of 2.0.

6. RESULTS

Magnetic gearing systems offer highly economical energy transfer and can achieve high transmission ratios at an increased torque density and an increased torsional stiffness. This particular 'smart' gearbox efficiently integrates the fundamental elements of gears (Mode1, rotating output shaft) and thereby adds some new functionality.

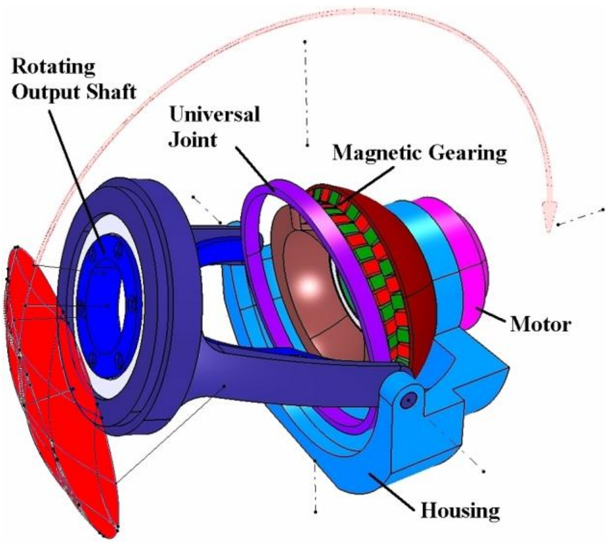

Figure 7. Magnetic Gearing Actuator with Deflected Output Shaft, Mode2 (Working Position).

Mode 2, the first additional function (Fig. 1, Fig. 7), allows inclination of the output shaft up to 30° (cardan) or 45° (homokinetic) during operation in fully functional mode. The deflection of the output shaft is available in two directions (β_y, β_z) and adds two degrees of freedom (DOFs) on the output shaft. It is shown as a red coloured region in Fig. 7, in which only one additional DOF is displayed.

Mode 3 is restricted to universal joints with a crosspiece only. The output shaft can be deflected along the red coloured line (Fig. 8) beyond the maximum inclination angle (cardan). Total deflection of the output shaft up to 180° is possible. As seen in Fig. 8, Mode 3 provides no further rotation of the output shaft and exceeds the fully operational mode.

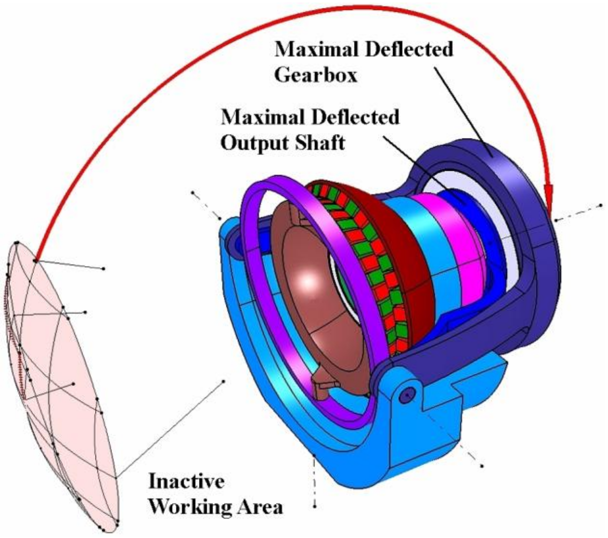

Figure 8. Magnetic Gearing Actuator with Totally Deflected Output Shaft, Mode 3 (Non-functional).

7. CONCLUSIONS

A new layout of magnetic gears is proposed. This design reduces weight of the magnetic circuit and therefore enables a much higher torque density, which is highly beneficial. Reduction to one single pair of magnetic wheels influences the torsional stiffness in a positive manner. A multiplication of the stiffness by a factor of 2 can be obtained.

The change of the internal design, rather than magnetic properties, leads to completely new possibilities of arranging mechanisms. Coaxial alignment of the input shaft and output shaft is possible but no longer restricted. Instead, angular displacement of the output shaft is enabled up to 45° and adds two degrees of freedom to the output shaft. Despite these additional degrees of freedom, the hollow shaft remains unaffected. One special arrangement of the internal gear components supports complete deflection of the output shaft up to the opposite direction. Both effects give way to new smart designs in space applications. Mechanisms designed for folding movable structures or for pointing tasks are potential areas of application on satellite platforms.

Besides, all smart properties of magnetic wobbling gears stay untouched. Because of the absence of mechanical contact, the gear delivers constant precision, performs consistently without lubrication, acts naturally as a clutch at overload conditions and subsequently remains fully functional.

8. REFERENCES

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