TORQUE-ENHANCING TECHNOLOGY IN MAGNETIC WOBBLING GEARS

Gregor Puchhammer

Karl Rejlek GmbH, Kirchfeldgasse 69, 1230 Vienna, Austria, Email: g.puchhammer@rejlek.at

ABSTRACT

The maximum available output torque in relation to weight or diameter is one of the major key features of gears. Torque-enhancing technology is a new method of stimulating extra torque out of a given total volume in magnetic wobbling gears. Torque-enhancing technology solely focuses on air gap regions where positive torque generation is insufficient. It converts regions with weak magnetic coupling into magnetically highly active zones. In areas of weak, zero, or negative integral magnetic interaction, existing permanent magnets are shortened in length. In exchange, permanent magnets with new magnetic orientations are placed in the formerly magnetic ineffective zones. The usage of more magnetic material in combination with a modified magnetic pattern leads to a tremendous increase in output torque.

1. INTRODUCTION

In magnetic wobbling gears (MWGs), the air gap between all magnetic interacting wheels is spherical in shape. Output torque is a result of global magnetic flux between these wheels. The intensity of the local magnetic flux differs very strongly depending on the location of interest. Large areas are magnetically very active and therefore, generate huge amounts of valuable torque. Other areas are unproductive without torque contribution. In fact, a few areas can even weaken the available torque on the output shaft.

To gain better insight into the working principle of the torque generating mechanism of MWGs, a new method for studying magnetic flux densities inside the air gap region is necessary. Since the motion of the magnetic wobbling wheel itself is three-dimensional, it is useful to introduce the idea of integral torque generation. The specific torque contribution of a finite magnetic element located on the wobbling wheel is derived by summarizing the fluctuating magnetic flux intensities of this finite element during one complete revolution of the input shaft. With this method, it is possible to get a clear impression of the torque contribution of different magnetic cross sections.

2. BASIC DESIGNS OF MWGs

As reported previously [1], three different MWG designs have been proposed, Types A, B, and C. Each of these designs addresses a special purpose. Type A is characterized by one single magnetic coupling between two magnetic wheels, resulting in maximized torque stiffness and density. This type is a good choice for gear stages that provide strong and powerful output shaft motion. Dewobbling motion on the output shaft is achieved with a universal joint.

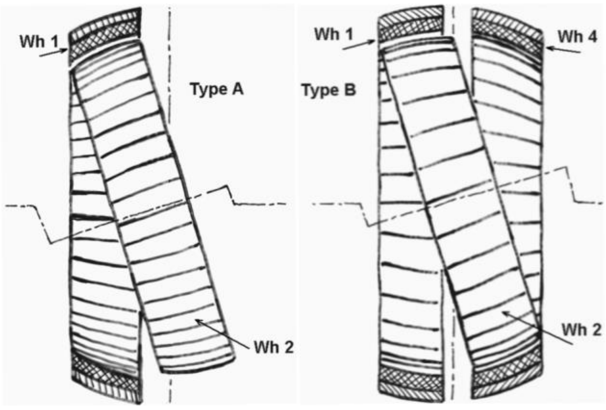

Figure 1: MWG Types A and B.

Type B MWGs are characterized by a hybrid approach which combines both a magnetic gearing and magnetic coupling stage. Within this three-wheel design, the stages are internally connected by the magnetic wobbling wheel.

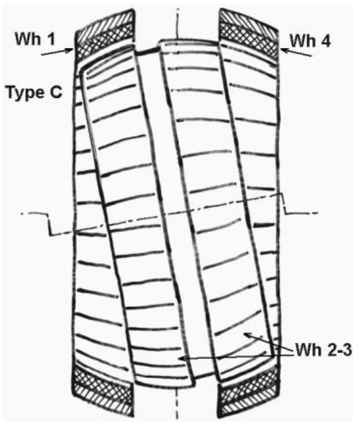

Figure 2: MWG Type C.

Despite having less angular stiffness than Type A MWGs, the dewobbling motion is realized in a quite simple and smart mechanical manner.

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Type C MWGs are characterized by exploitation of the whole gearing potential if the maximized reduction ratio is required. In this type, an additional fourth magnetic wheel (Fig. 2) is merged onto the magnetic wobbling wheel so that the inherent gearing mechanisms can be used twice. At its best, multiplication of both reduction ratios can be achieved, resulting in extremely high gearing ratios in only a single gear stage. Besides the rotating input and output shafts, the whole gear mechanism functions with only a single moving part, the wobbling wheel.

3. MAGNETIC INTERACTION OF A SINGLE MAGNETIC WHEEL PAIR

The idea of torque-enhancing technology (TET) has emerged due to interchangeability considerations. It was triggered by the desire to exchange existing conventional gearboxes with magnetic ones. As a consequence, higher torques have to be generated in the same gearbox volume or diameter.

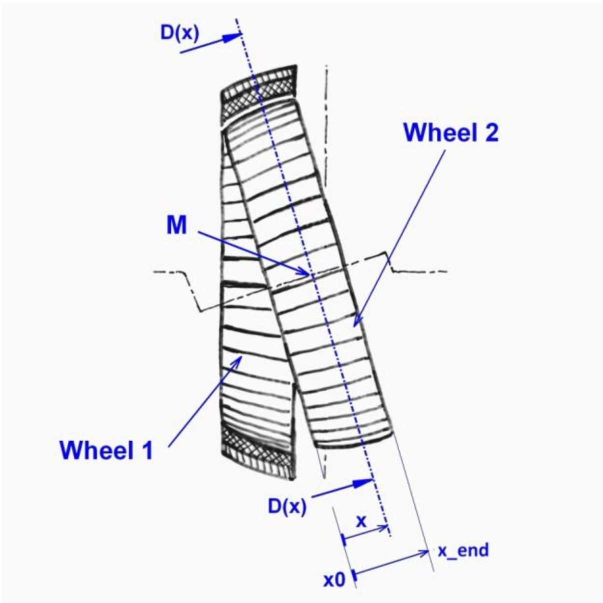

Figure 3: Schematic of cross-section D-D in the axial position starting from x0 to x_end.

The best way to explain TET function is to look at the magnetic interaction of a single magnetic wheel pair without TET (Fig. 3). The number of pole pairs on Wheels 1 and 2 differs, with the difference between them being at least one or more. As shown in Figure 3, not all magnets placed on one magnetic wheel face have a magnetic counterpart on the other magnetic wheel. For the purpose of high magnetic coupling and resulting torque generation, these free regions are undesirable because they do not contribute to the possible magnetic interaction.

On the other hand, the free region is crucial for proper gearing function, and it characterizes the major principle for all magnetic gearing designs. To induce magnetic gearing, it is necessary to pull the interacting magnets out of their magnetic coupling in order to put magnetic clearance between them. It is also necessary to push them back again into a modified position. In MWG, this fundamental motion of magnets is enforced by the wobbling kinematics in a mainly tangential manner.

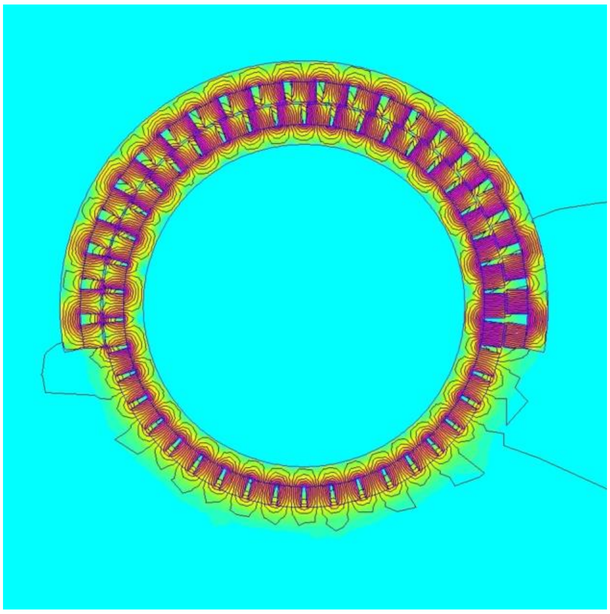

Figure 4: Magnetic flux density of cross-section D-D at axial position x.

Calculation of magnetic flux densities (Fig. 4) at all consecutive cross-sections of the wobbling wheel gives good understanding and insight into the characteristics of MWGs.

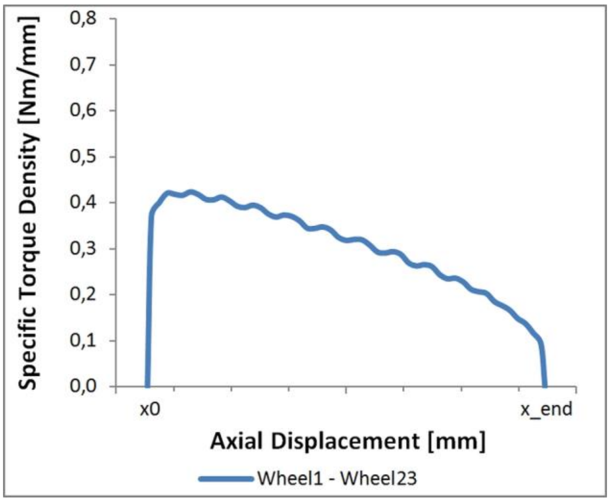

Figure 5: Specific torque densities along cross-section DD(x) at axial position x0 to x_end.

These cross-sections are obtained by starting at displacement x0 and passing along the axis of wobbling Wheel 2 up to the final displacement x_end. In Figure 5, the overall or integrated specific torque density of each cross-section is plotted over the axial length of the wobbling wheel. These cross sections are placed at right-angles to the axis of Wheel 2 and therefore, are inclined with the wobbling angle to the gearbox casing axis.

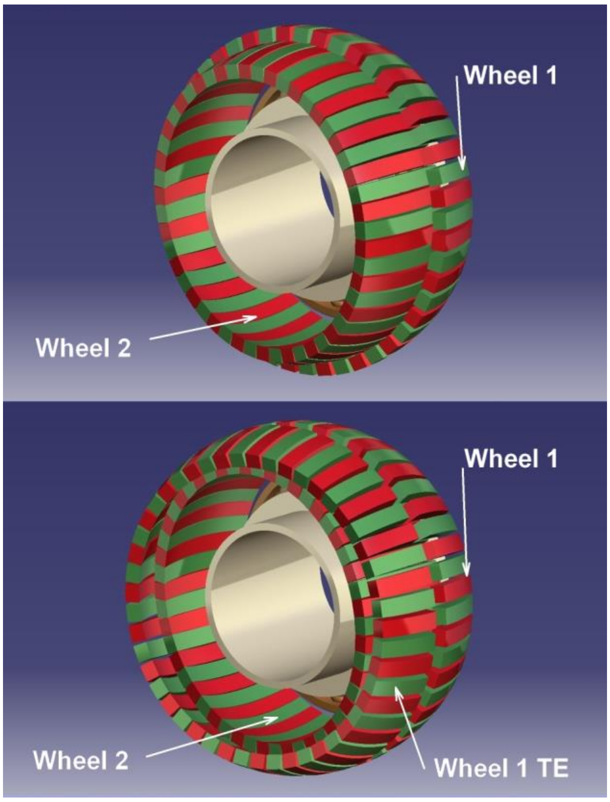

Figure 6: MWG Type A.
Upper side: without torque-enhancing wheel
Lower side: with torque-enhancing wheel

As realized in the early prototypes, one way to maximize the output torque of Type A-shaped MWGs is to adapt the wobbling angle and axial length of the wobbling wheel. Although quite good results were achieved, this design is limited by the spherical shape of the air gap. The longer the axial length is extended to both ends of the sphere, the more the magnets are extended to the sides where the diameter becomes smaller and the magnetic interaction becomes less effective. The spherical torque will increase less and less at the cost of torque density, which will start to decrease slightly. This is one natural limit to maximizing the total harvestable torque.

4. TORQUE-ENHANCING MAGNETIC WHEEL

A closer examination of the regions worst suited for torque generation shows an area without any geometric overlap between the magnetic wheels. Parts of Wheel 1 are out of alignment with Wheel 2 (Fig. 3). This can also be seen in the cross-sectional view presented in Figure 4, where the lower part of Wheel 2 has no magnetic counterpart on Wheel 1. If this area were filled with magnets, it would contribute to local negative torque and therefore, reduce the overall torque. This region is of interest in TET.

The above-described disuniting and uniting motion of the single magnets on the interacting magnetic wheels needs space for shifting. Therefore this space must be kept free from magnets. This location generally would be best suited for magnet placement aiming at strengthening magnetic interaction, but it is not available.

Besides the method of optimization described for Type A MWGs, torque enhancement can also be achieved by adding an additional magnetic wheel.

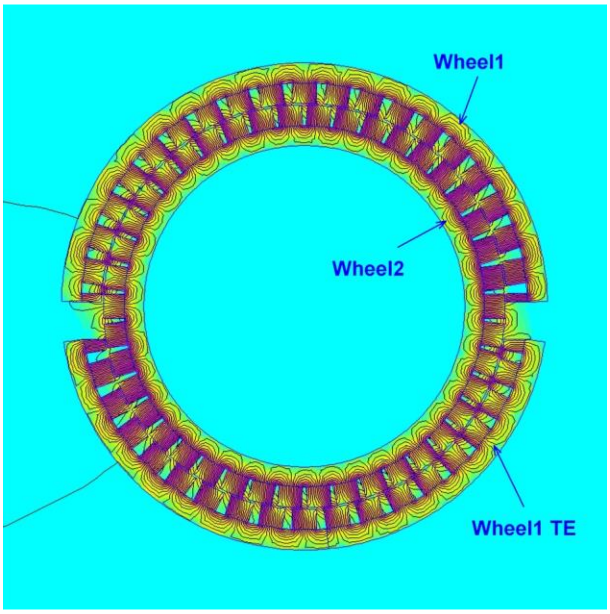

Figure 7: Magnetic flux density of triple Wheel 1-Wheel 2-Wheel 1 TE MWGs.

The Type B MWG presented in Figure 2 shows a hybrid gear with one gearing and one coupling stage. This scheme is very similar to Type A MWGs with TET. However, two design changes have to be made. Wheel 4 must become fixed to Wheel 1, thereby becoming part of Wheel 1. Both Wheels 4 and 1 must have the same number of pole pairs, and the magnetic orientation of Wheel 4 must be twisted by 180^{o}. Wheel 4 with these adaptions will hereafter be referred to as “Wheel 1 TE.” As a result, the polar arrangement of wobbling Wheel 2 faces its magnetically active counterparts (Fig. 6, lower side). Addition of Wheel 1 TE doubles the resultant torque compared to the configuration of a single magnetic wheel pair (Fig. 6, upper side). Despite the doubled output torque, the torque density increases only slightly. As seen in Figure 7, the magnetic flux density between Wheel 2 and Wheel l TE is nearly identical to the original flux density of Wheels 2 and 1.

5. RESULTS

The geometry of the magnetic wheel arrangement chosen as the computational basis for the example in Figure 6 is a fully symmetric one. The middle M of wobbling Wheel 2 is located in its symmetry plane and coincides with the main axis of the gear housing. Wheel 2 is inclined by the wobbling angle. Torque-enhancing magnetic Wheel 1 TE is a copy of magnetic Wheel 1, mirrored on the symmetry plane of the gear arrangement.

Figure 8 shows three different specific torque densities along the axial length of wobbling Wheel 2. The blue line is the original specific torque density without the torque-enhancing contribution of Wheel 1, as already shown in Figure 5. The dashed green line in Figure 8 is the additional, symmetric torque contribution due to Wheel 1 TE.

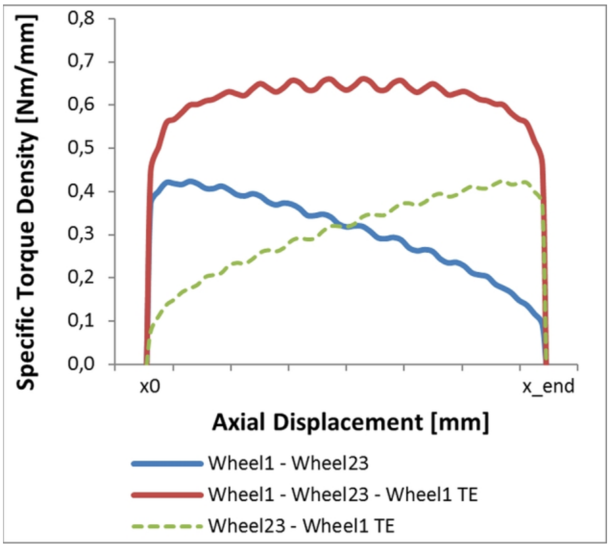

Figure 8: Specific torque densities along cross-section DD(x) at axial position x0 to x_end.

Because Wheel 1 and Wheel 1 TE are acting on the same wobbling wheel (Wheel 2), additional torque will be generated on wobbling Wheel 2. The spherical all-over torque is doubled, as well as the mean value of the specific all-over torque density on the wobbling wheel (Fig. 8, brown line). In gear box designs without symmetrically arranged magnetic wheels, TET will lead to similar results, but the symmetry in specific torque densities will no longer exist.

Although the example in Figure 8 was only performed on a single pair of magnetic wheels (if we define Wheel 1 and Wheel 1 TE as one single magnetic wheel), the proposed method of torque enhancement can be applied to every magnetic wheel couple. Clearly, application of TET to Type B and C MWGs can produce exiting magnetic patterns on the magnetic wheels. The mechanical simplicity and the simple set-up of the gear box is not affected by this modification of the magnetic wheels.

6. CONCLUSION

The new method of additional torque harvesting by means of TET leads to a tremendous increase in MWG output torque. Any application suffering from restrictions in physical dimensions will profit from TE technology. It is therefore well suited if interchangeability of gear boxes is of concern. On the other hand it reduces the necessary dimension of MWGs in applications constrained in weight or in available space. Beside these facts, TET increases the synergistic effect of higher torque density.

Modification of magnetic interacting wheel pairs is done by expanding the magnetically active areas and by modifying these areas into highly active magnetic zones. Consequently, these zones are characterized by new magnetic patterns. TET in MWGs is one step further on the way to better, smaller, and smarter magnetic gear boxes in every field of industry. In addition to state-of-the-art gearboxes, the special, smart magnetic properties of MWGs will follow.

7. REFERENCES

1. Puchhammer, G. (2014). Magnetic Gearing versus Conventional Gearing in Actuators for Aerospace Applications. In Proc. 42nd Aerospace Mechanisms Symposium, NASA/CP–2014-217519, pp175-182., Baltimore, Maryland

For further information about magnetic gearing, please contact:

Dr. Gregor PUCHHAMMER
Karl Rejlek GmbH
Tel: +43 1 982 1678 125
Email: g.puchhammer@rejlek.at