Dynamic simulation of a coaxial magnetic gear using global ODE's and DAE's and the rotating machinery, magnetic interface

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Introduction

The coaxial magnetic gear is an attractive alternative to classical mechanical gears. Due to torque transmission based on magnetic forces the coaxial magnetic gear acquires valuable advantages over the mechanical gears, i.e., high mechanical durability, overload protection and lower noise [1, 2]. Currently, the investigations of magnetic gears enhanced considerably in the last decades due to accessibility of strong permanent magnets [3]. For the designing and optimization of the magnetic gear, the numerical model becomes a useful tool. Although a fair amount of the numerical models of the magnetic gear are static [4-7], the dynamic characteristic of the magnetic gear can't be obtained from static models. Nevertheless, the latter can be used to simulate magnetic fields and mechanical forces in the steady state. To obtain the dynamic characteristics of the magnetic gear, such as run-up, slowing-down and load demand process is necessary to use a dynamic model of the magnetic gear. This designed dynamic model will be discussed further in the current paper.

For the numerical solution of the fore-mentioned dynamic model the Comsol Multiphysics® [8] is applied. The nonlinear material parameters, a small air gap size and transient dynamic simulation are considered in this two-dimensional numerical model. The discussed model allows to obtain all necessary effects except the end-effects, with the acceptable calculation time.

Set-up of the simulated magnetic gear

The coaxial magnetic gear is composed of three main parts (**Figure 1**): the inner rotor, the modulator and the stator. While the rotor and modulator are rotating, the stator of the magnetic gear remains in a fixed position. The modulator of the magnetic gear consists of 9 ferromagnetic segments. These segments are intended to modulate the magnetic fluxes between stator and rotor. To achieve mechanical stability non-magnetic segments fill in the spare places of the modulator. The stator is composed of 16 permanent magnets and the ferromagnetic ring. The ferromagnetic ring serves for

closing the magnetic fields between the permanent magnets within the stator. A permanent magnet with two poles is used as the rotor. The transmission ratio η_T depends on the number of magnetic poles in the rotor and in the stator and on the number of modulator ferromagnetic segments:

$$\eta_T = \frac{N_C}{N_R} = \frac{9}{1} = 9, \qquad (1)$$

where N_C is the number of the modulator segments and N_R is the number of the pole pairs of the rotor.

The air gap in this magnetic gear is 0.5 mm thin, which assists the high efficiency factor of the force transmission between rotor and modulator segments.
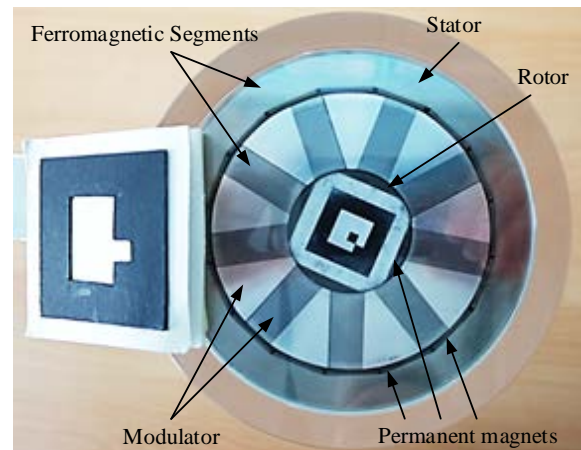

Figure 1. Magnetic gear

An angular velocity is predefined on the one of two rotating parts as an input parameter of the model. Due to this external angular velocity, one part of the gear rotates and the magnetic field configuration changes, which causes the magnetic forces. In turn, these forces cause a rotation of another rotating part of the gear.

Numerical model

The COMSOL Multiphysics ® is used to obtain a numerical simulation of the magnetic gear. The numerical model of the magnetic gear consists of two main parts: magnetic computation and mechanical computation. The two-dimensional model is adequate to investigation and verification of all necessary

parameters of the magnetic gear. The end-effects are ignored in this model to achieve an acceptable calculation times.

The geometrical scale in this model varies from mm in the air gap to several cm. For an accurate calculation of the magnetic forces it is necessary to generate an accurate mesh, especially in the air gap. The size of the triangle elements in the air gap is adjusted to obtain at least two elements in radial direction. The discretized model of the magnetic gear is depicted in **Figure 2**.
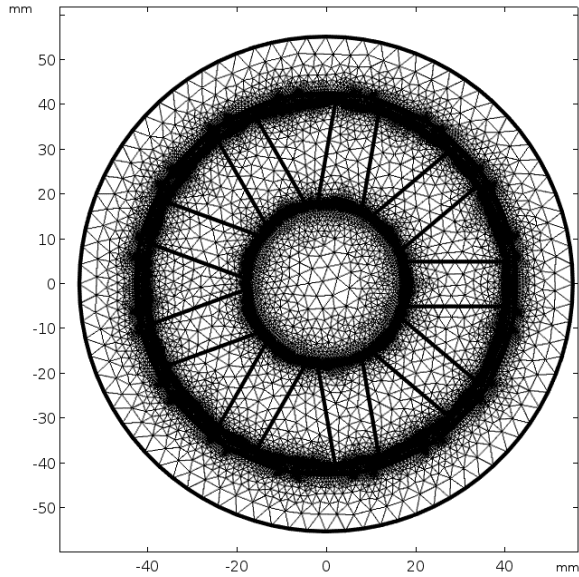

Figure 2. Discretized model of the magnetic gear

The discretized model consists of 41873 domain elements and 6627 boundary elements. The model is discretized using second order triangular elements.

The rotating machinery, magnetic interface (RMM) is used to simulate magnetic fields and forces. The magnetic scalar potential formulation is applied for the solution of the magnetic field problem.

As ferromagnetic material the soft iron is used with nonlinear HB-curve (**Figure 3**). The magnetic simulation is done excluding the eddy-current losses in the soft iron ($\sigma = 0$), since the magnetic gear consists of permanent magnets.
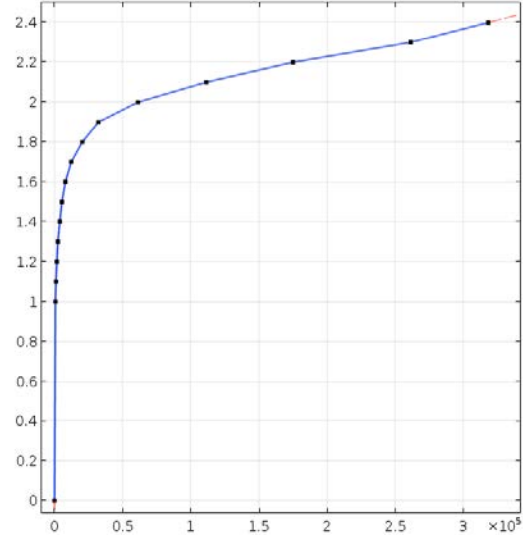

Figure 3. BH-curve of the soft iron

All other parts of the magnetic gear are simulated with electrical conductivity $\sigma = 0$, and relative permeability $\mu_r = 1$.

The constitutive relations and properties of the magnetic gear are defined with Ampere's Law. The parameters of the permanent magnets are defined with constitutive law:
$$B = \mu_0 \mu_r H + B_r, \tag{2}$$
where H is the magnetic field strength, B_r is the remanent flux density. The permanent magnets are homogeneous magnetized.

The remanent flux density for the stator magnets is defined in cylindrical coordinate system:
$$B_r = (\pm B_{rs}, 0,0), \tag{3}$$
where B_{rs} is the amount of the remanent flux density of the stator magnets.

The remanent flux density of the rotor permanent magnet is defined in Cartesian coordinate system.
$$B_r = (\pm B_{rr}, 0,0), \tag{4}$$
where B_{rr} is the amount of the remanent flux density of the rotor magnet.

The amount and direction of the remanent flux density are depicted in **Figure 4**, with the help of the arrow surface.
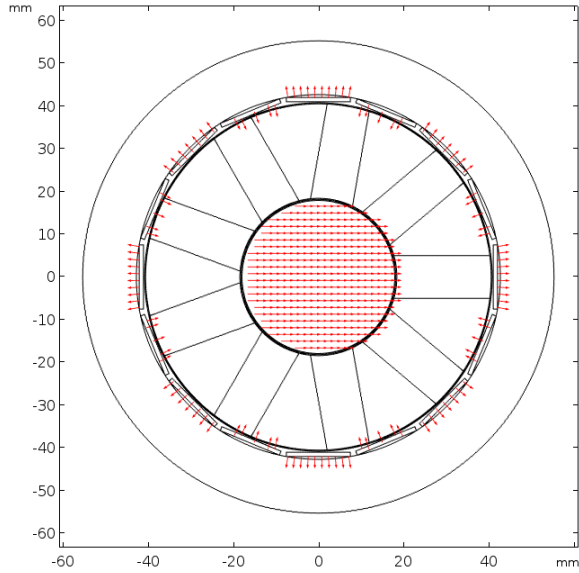
Figure 4. Predefined remanent flux density

Although the magnetic gear consists of rotating and stationary parts to avoid remeshing after each time step the identity pairs are employed. The fore-mentioned pairs connect the rotating rotor part with rotating modulator part and rotating modulator part with stationary stator part. The blue lines in **Figure 5** represent the identity pairs.
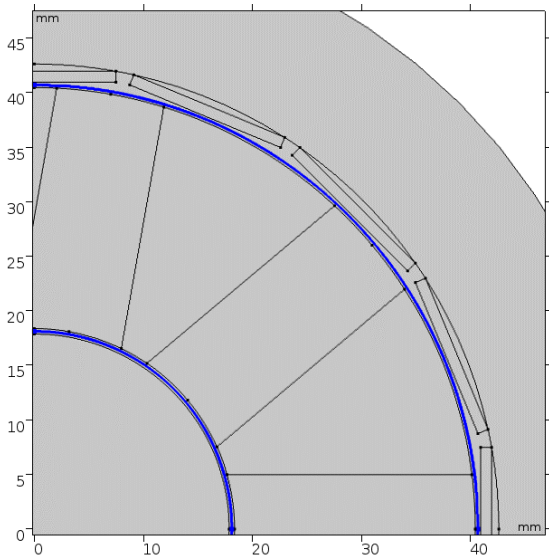

Figure 5. Identity pairs

The continuity node in rotating machinery, magnetic (RMM) interface is used to enforce continuity of the field variables across the defined identity pairs.

The mechanical computation is done with global ODE's and DAE's (GE) interface.

The torque $\boldsymbol{\tau}$ is calculated with a help of the Maxwell Stress Tensor:

$$\boldsymbol{\tau} = \int_{\Omega} d(\boldsymbol{r} - \boldsymbol{r}_0) \times (\boldsymbol{n}T)dS, \qquad (5)$$

where $\boldsymbol{r}_0$ is position vector, $\boldsymbol{n}$ is a normal vector, T is a Maxwell Stress Tensor, S is a surface, Ω is the volume.

An axial torque τ_{ax} is necessary for the calculation of acceleration:

$$\tau_{ax} = \frac{\boldsymbol{r}_{ax}}{|\boldsymbol{r}_{ax}|} \cdot \boldsymbol{\tau}, \qquad (6)$$

where $\boldsymbol{r}_{ax}$ is an axial position vector.

The axial torque can be obtained direct from the RMM interface.

The angular velocity of the rotating part ω_r (in this case rotor) is calculated with:

$$\frac{d\omega_r}{dt} = \frac{\tau_{ax}}{I}, \qquad (7)$$

where I is inertia torque.

The inertia torque is calculated in the variable definitions with a help of the integration component coupling:

$$I = \int_V \boldsymbol{r}_{\perp}^2 \rho(\boldsymbol{r})dV, \qquad (8)$$

where $\boldsymbol{r}_{\perp}$ is perpendicular part of the position vector to the rotation axis, $\rho(\boldsymbol{r})$ is the density, V is the volume.

The rotation angle of the rotor φ_r and modulator φ_m is calculated with:

$$\frac{d\varphi}{dt} = \omega, \qquad (9)$$

The complete model is calculated using a time-dependent solver. The system of the nonlinear equation is solved at each time step using a nonlinear solver with a damped Newton termination method. Time-dependent solver is multifrontal massively parallel sparse (MUMPS) direct solver, the time stepping method is a backward differential formula (BDF).

Magnetic and Mechanical calculation results

As the first step, the stationary simulation of the magnetic gear is computed. In this simulation the modulator and stator are taken as a stationary part. The angular velocity of the rotor is predefined as 2π rad s^{-1}.

The calculated absolute value of the magnetic flux density at the time step t=0 s is depicted in **Figure 6**.
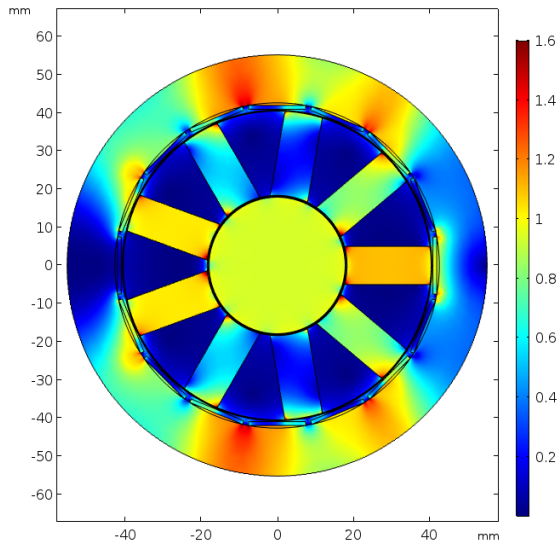
Figure 6. Magnetic flux density at initial time step

As result of this simulation the axial torque of the magnetic gear is obtained depending on the rotation angle of the rotor. Axial torque in the case of a blocked modulator and a rotating rotor is depicted in **Figure 7**
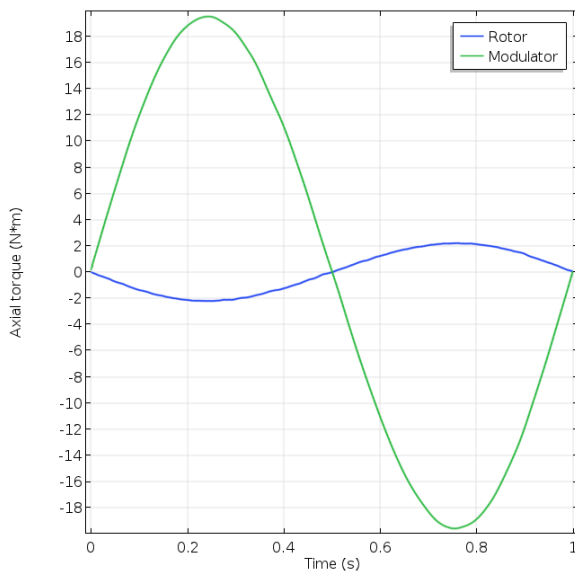

Figure 7.Axial torque

The absolute value of axial torque of the modulator is 9 times higher than the absolute value of axial torque of the rotor. This simulation shows that the obtained transmission ratio concur with the calculated transmission ratio in the equation 1.

The system of the nonlinear equations with 86524 unknowns was solved using time-dependent direct solver. The computation time took 13 minutes on 4 cores of an Intel Core i7-7770 processor with 3.6 GHz. The memory requirements were 1.4 GB

The second step of the magnetic gear analysis is the dynamic simulation of the magnetic gear. In this case the angular velocity of the modulator is predefined, i.e., a modulator is connected to the motor in reality. To achieve a realistic acceleration of the modulator the necessity of time-dependence of the run-up part of the predefined angular velocity arises (**Figure 8**).
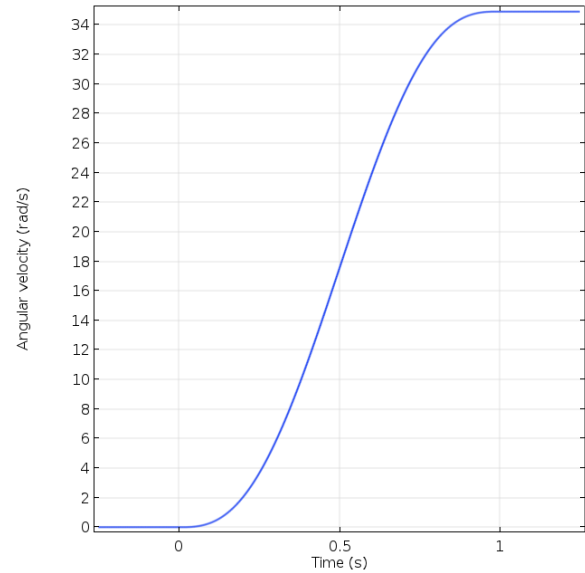

Figure 8. Predefined angular velocity of the modulator

The calculated angular velocity of the rotor in case of the predefined angular velocity on the modulator is depicted in **Figure 9**.
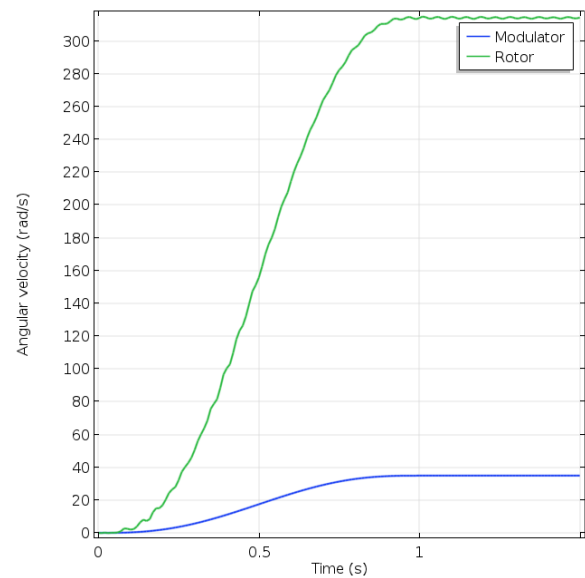

Figure 9.Angular velocity

Thus the gained transmission ratio corresponds to 9. It means that the acquired transmission ratio from this dynamic simulation correspond with the fore-

mentioned transmission ratio from the stationary simulation and equation 1. The computation time took 5 hours 35 minutes.

Conclusions

A model for the dynamical calculation of the magnetic gear has been introduced. The COMSOL Multiphysics ® was used to obtain a numerical solution of the fore-mentioned model. This model allows calculation of the magnetic gear in stationary and dynamic cases. The magnetic forces and magnetic fields are obtained from rotating machinery, magnetic (RMM) interface. The angular velocity in the dynamic case is obtained from general ODE's and DAE's (GE) interface. With the help of this model a dynamic run-up process and stationary characteristics of the magnetic gear were simulated.

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