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Introduction to COMSOL based Modeling of Levitated Flywheel Rotor

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Abstract: This elaboration presents a pre-study on automatic rotor construction for the flywheel energy storage system dedicated to operate in the levitation mode. The optimization profile model is used as a basic profile source. A special attention is paid to moment of inertia and stress factor. The 3D flywheel shape is generated on the base of obtained profiles. Eigenfrequencies are calculated to validate the operation in rigid mode. A steel and aluminum based constructions of the considered rotors are compared. The energy stored in the flywheel is calculated and plotted with respect to the angular velocity. The automatic generation of radial active magnetic bearing construction is presented and linked with the flywheel problem. The pre-study for the application of levitation components is provided to point out important aspects of the interdisciplinary flywheel based energy storage system design and analysis.

Keywords: Flywheel, active magnetic bearing, COMSOL/MATALB programming.

1. Introduction

The flywheel energy storage systems becomes popular due to the new material technologies, power electronics, control systems, and bearings. Nowadays, they transformed from pure mechanical devices to modern mechatronic devices. The modern flywheels will operate with very high rotational velocity applied to rotor with a relatively small units manufactured with optimal shape tuned for light and strength materials. The best materials are composite one, that are characterized by low density and high tensile strength. Therefore they enable higher rim speeds than steel rotors allow. For the demonstration purposes and practice with rotor dynamics the aluminum and steel rotors are still popular.

The flywheels equipped with AMBs [14] are developed for many years. One can find a number of prototype applications and flywheel configurations [3, 4, 6-9]. The main feature of AMB is a mechanical frictionless operation. It allows to obtain high rotational speeds and control the levitated rotor dynamics. A number of research is being done in this field including material, construction, power electronics and control systems aspects. A number of problems becomes active: eddy current losses, thermal losses , power consumption of AMB actuators and control system, integration with flywheel, application of optimal motor/generator. It is observed that there is a request to collect all existing features and limitations in one place (modeling and prototyping environment) [10].

With this research the flywheel profile for the application of two radial AMBs will be considered. To operate with AMBs the ferromagnetic rotor must be used. It can be achieved in two typical forms: solid steel rotor or steel/electrical sheet rings. The second solution allows to minimize looses and to build up flywheel rotor using different materials.

2. Flywheel generation

The Optimizing Flywheel Profile COMSOL model [2] presents a method to perform shape optimization of the flywheel profile. The aim of the optimization stage is to find flywheel's profile with a radial stress distribution that is as even as possible under the design requirements of specified initial flywheel mass and moment of inertia calculated for the basic geometry (in a ring form). The full mathematical and modeling description of the flywheel profile optimization problem is given in [5].

This model has been used initially to compare profiles obtained for a two typical materials used at the prototyping stage (easy and cheap for prototype manufacturing) to practice with flywheel dynamics. The aluminum and steel materials as well as different rotating speeds in the range of 3000÷15000rpm were considered. The COMSOL model has been used with the modified initial parameters: inner flywheel radius (r = 2.5mm), outer flywheel radius (r_1 = 120mm), initial flywheel thickness (H_0 = 4mm), flywheel thickness constraints ($H_{min} = 0.25H_0$, $H_{max} = 5H_0$). The aluminum and steel material properties are summarized in table 1 and the optimization results as flywheel top cross-section profiles are presented in Figure 1 respectively.

Table 1: Selected properties of the considered materials

	Aluminum	Steel	Unit
Young's modulus	$70 \cdot 10^9$	$205 \cdot 10^9$	N/m^2
Poisson's parameter	0.33	0.28	
Density	2700	7850	kg/m^3

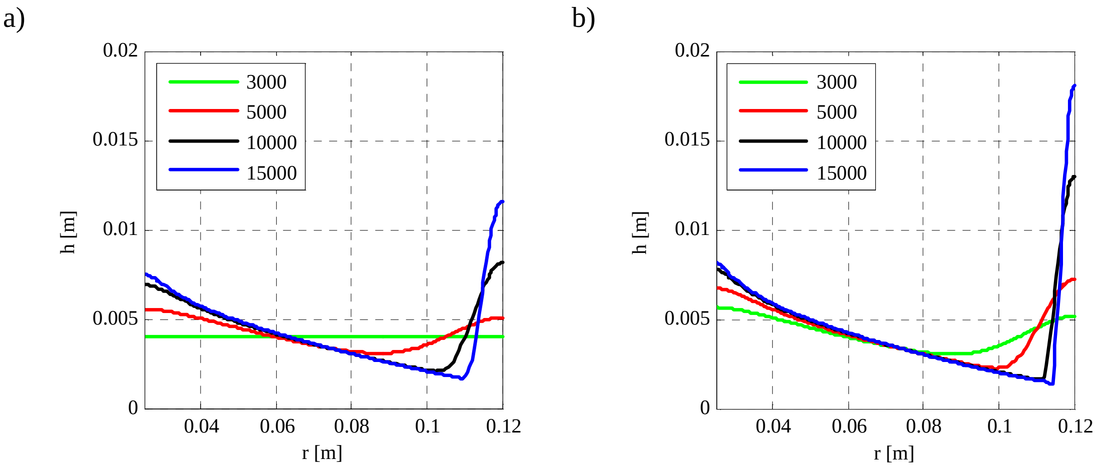

Figure 1. Flywheel profiles for a different rotational speeds given in rpms. a) aluminum; b) steel.

During the optimization stage the flywheel mass and inertia moment remains unchanged. For the same geometry constraints two different flywheels were obtained depending on the selected material and rotational speed. The optimized profile is characterized by the flat stress and lowest values at the flywheel center than initially assumed (see Fig. 2).

The original files were modified to the function form for the optimization purposes and direct execution in MATLAB. The optimization procedure returns the optimal flywheel profile in a form of line segments. Number of them depend on the optimization algorithm settings and can reach a value of hundreds. The main problem appears when the rotor is meshed. Due to the large number of line segments in the flywheel profile, the number of generated mesh elements is extremely large. To minimize this undesirable effect the flywheel profile must be reorganized. It is done by the polynomial approximation of the profile and appropriate selection of points in the radial direction. For example, the generated profile of the aluminum disk and desired rotational speed of 5000rpm consist of 211 points. It gives the mesh of 410708 elements. With the proposed approach the profile is limited to 39 points and mesh to 10984. On the base of obtained flywheel profile the total mass and moments of inertia were calculated and are summarized in table 2.

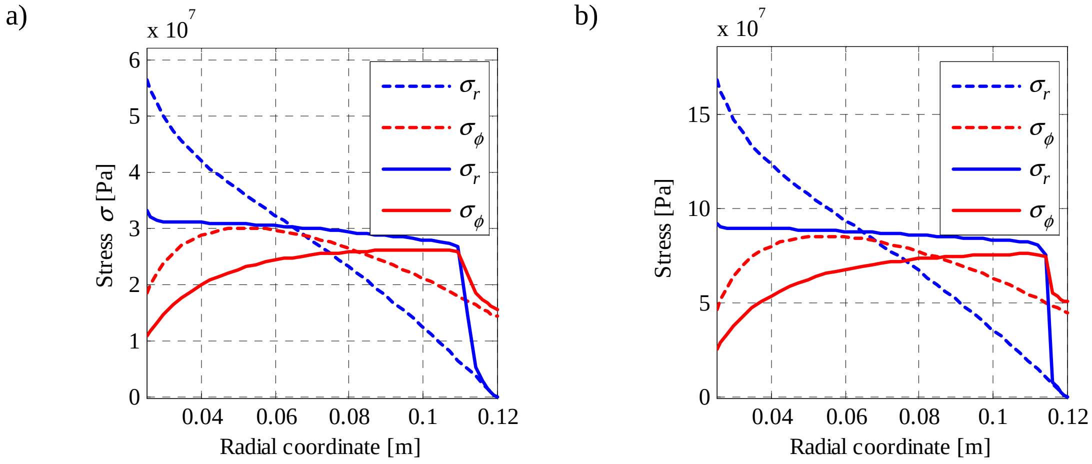

Figure 2. Radial (blue) and azimuthal (red) stress components for initial (dashed line) and optimized (solid line) flywheel profiles calculated at 1500 rpm. a) aluminum; b) steel

Table 2: Mass and moments of inertia of the considered rotors

Item	Aluminum rotor	Steel rotor	Unit
m	0.4673	1.3588	kg
J_{XX}	$1.756{\cdot}10^{-3}$	$5.106{\cdot}10^{-3}$	m^2kg
J_{YY}	$1.756{\cdot}10^{-3}$	$5.106{\cdot}10^{-3}$	m^2kg
J_{ZZ}	$3.511{\cdot}10^{-3}$	$10.208{\cdot}10^{-3}$	m^2kg

With such a flywheels the stored energy $E = 0.5J_{ZZ}\omega^2$ is plotted in Fig. 3 with respect to the rotational speed and reaches the 4.33 kJ and 12.59 kJ at maximal speed of 15000 rpm.

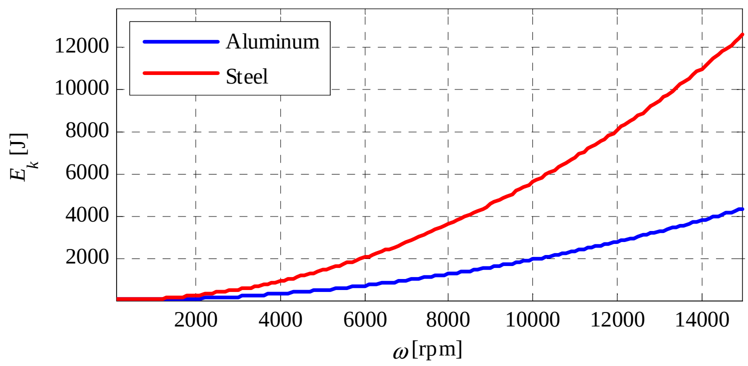

Figure 3. Energy stored with respect to the rotational speed for the considered flywheels

3. Radial Active Magnetic Bearing generation

To stabilize the rotating flywheel two radial AMBs are proposed. They position is determined by the location of ferromagnetic rings at the rotor and the AMB size (see Fig. 5a). To obtain the AMB configuration the custom COMSOL/MATLAB function for AMB code generation was used. The AMB geometry is generated with the support of Bézier curves [12]. The stator and coils geometries are generated automatically in the 2D plane. The forces generated by AMBs must compensate rotor reaction forces. Therefore the proposed method for AMB synthesis is well applicable at the optimization stage [11]. The classical form of generated heteropolar four electromagnets construction is presented in Fig. 5b.

4. Automatic set-up of flywheel components

To build a complete flywheel rotor on the base of optimized profile a set of custom operations is required. The obtained profile is used to generate the 3D flywheel shape. Additionally flywheel rotor and ferromagnetic rings are added for the radial AMB purposes. All of them are realized in an automatic way with the support of user-defined COMSOL/MATLAB code. The automatic generation flow chart is given in Fig. 4.

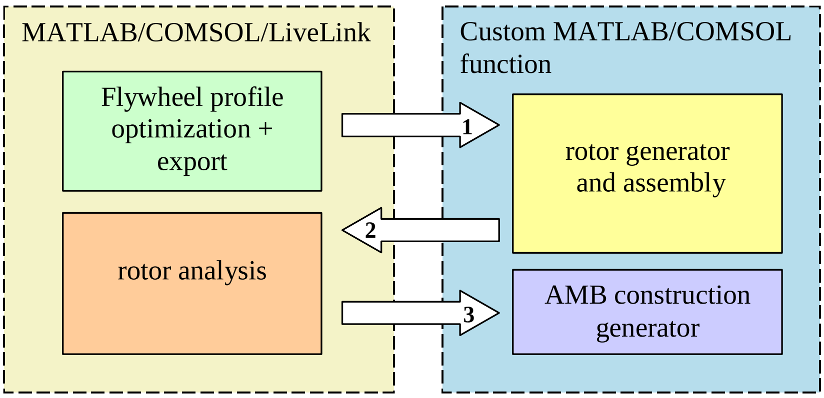

Figure 4. Path for automatic generation of flywheel components.

The complete flywheel rotor is presented in Fig. 5a. It is assumed that in the vertical axis the passive magnetic suspension is realized at the bottom part and hybrid magnetic suspension at the top.

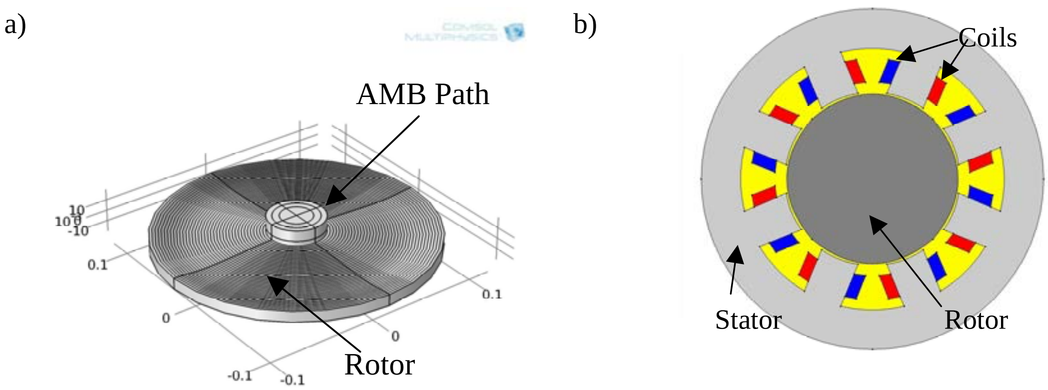

Figure 5. Generated geometries: a) complete flywheel rotor; b) AMB

The obtained profile is used to generate the complete flywheel rotor. In this case the optimal profile has been exported from the solved model and processed by the custom COMSOL/MATLAB function to obtain a complete rotor geometry. Two ferromagnetic rings for the AMB purposes were added. The rotor profile is customized and assembled with the flywheel for analysis purposes.

3. Eigenfrequency analysis with flywheel placed on the rotor

Using COMSOL Eigenfrequency mode and Solid Mechanics toolbox the problem has been solved obtaining rotor eigenfrequencies of 762.8, 763.2, 814.8, 906.6, 906.9, and 1633.9 Hz. The Problem has been solved at the considered lowest and highest rotational speed to diagnose rotor displacement. The total displacement quantity given in [nm] and surface deformation are presented in Fig. 6. With this mode the rotor construction is validated. The rotor remains rigid in the whole range of given frequencies. It is requested to construct the flywheel as rigid body because a number of control, sensing and construction problems is eliminated.

a) b)

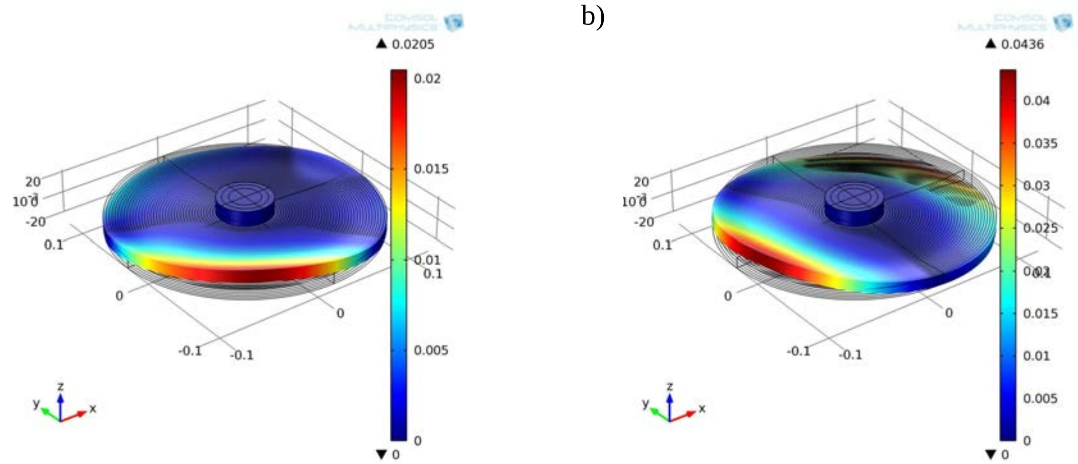

Figure 6. Surface displacement for rotational speeds: a) 3000 rpm; b) 15000 rpm.

4. Other aspects

To complete the flywheel construction the PM brushless motor/generator, power electronics for energy management and control system including control algorithm must be considered. The aerodynamical effect, electromagnetic field and rotor dynamics must extend the designed mode to obtain a complete virtual prototype. On can see that the model will be very complex. Such obtained virtual prototype will be useful for the optimization tasks.

5. Conclusions

With this paper a concept of the levitated flywheel has been presented. One can see that, there are many possible solutions of such device. The COMSOL Multiphysics software allows to provide a number of research to find an optimal configuration of the complete system. Thanks to the COMSOL/MATLAB programming features it was possible to develop a method for automatic generation of the flywheel rotor geometry as well the AMB construction.

Observing the presented design path one can find that the best way is to develop a complete parameterized model and perform global optimization including geometry, materials and control tasks. Such complex model should be realized in a form of 3D virtual prototype with moving mesh mode for levitation [13] and rotation purposes. In this case, thanks to the controlled levitation the complete rotor dynamics could be steered and validated at the simulation stage.

A number of problems like eddy current looses, aero-dynamical properties of the levitated rotor, power electronics should be considered, too. The design of the levitated flywheel looks to be a complex task and require synergy of knowledge, experience and researchers in many fields. Joining them with the support of COMSOL Multiphysics it will be possible to build a complete flywheel virtual prototype and obtain a device with a highest efficiency.

8. References

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