

Coupled Mechanical and Electromagnetic Optimization of High Speed Rotors

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Abstract—Optimizing mechatronic systems is of increasing importance, for example, to minimize the consumption of resources and energy during operation and production. The optimization objectives for rotordynamic systems are, for instance, critical resonances, durability and costs. In order to meet such objectives, good optimization algorithms as well as simulation tools for each physically relevant effect for the problem are required. In this paper, we present the coupling of the optimization software MagOpt and the mechatronic simulation tool HOTINT and an application of the system.

I. INTRODUCTION

For the coupled optimization of a magnetically levitated high speed rotor, it is necessary to consider vibrations and eigenfrequencies, mechanical strains, high efficiency and bearing design.

There exist specialized tools for specific physical effects, such as simulation programs for mechanics, electromagnetics, thermal or fluid problems. For simulating an electrical machine, the different specialized tools have to be coupled.

There already exist commercial solutions that can be used for multiphysics optimization, e.g., the multiphysics software ANSYS together with a third party optimization tool. In [1] the optimization of the acoustic behavior of electrical drives with these programs is described.

The main benefits of using a small open source program like HOTINT [2] are the flexibility of code that allows quick customization of the program for the specific problem. Furthermore small programs can be distributed over a cluster of computers for parallelized optimization, as done by MagOpt [3].

II. THE MULTIBODY SIMULATION SOFTWARE HOTINT

HOTINT is an open source engineering software based on a redundant multibody formulation. The work on this program started in 1997 and is continually developed further as joint project of LCM and Johannes Kepler University Linz. The software contains all features which are necessary to compute the quantities relevant for the optimization, such as the mechanical stresses due to centrifugal forces or critical resonances. Besides these necessary requirements HOTINT offers some key advantages over the available commercial programs. For instance, the program offers an easy-to-write scripting language and has an open architecture. Therefore, coupling the program with external software is especially easy, either through input parameters or through C++ code or

the TCP/IP interface.

HOTINT provides a large variety of flexible and rigid bodies in 2D and 3D. Those can be connected via flexible and rigid joints in Lagrange or penalty formulation including nonlinear joints such as contact or friction. Additionally the user can include different sorts of loads and sensors into the model as depicted in Fig. 1. HOTINT is easy to extend, so if a particular object is not available yet, the comprehensive manual and the structured code enables the user to adapt existing objects or to implement new objects in short time. After the optimization of the considered rotor is finished, HOTINT can also perform post-processing computations, e.g., model the controller with IO-elements in order to test its functionality, or do a parameter variation to generate a Campbell diagram. A fully dynamic run-up of the rotor can be simulated to verify the simulation results with measurements of real experiments.

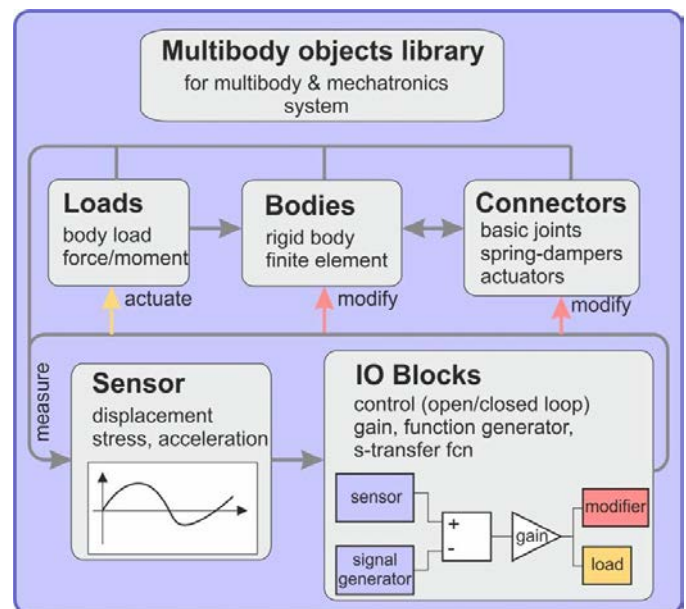


Figure 1. Structure of a HOTINT model.

III. THE OPTIMIZATION TOOL MAGOPT

MagOpt is an abbreviation for “Magnetic Optimization” and is a software package that does not only include magnetic optimization but also general simulation- and optimization-

tools in connection with mechatronic components and electrical machines in particular.

Starting in June 2008, the MagOpt project was continuously enhanced and contains modules for electromagnetic, thermal and circuit simulation today. A post processing toolbox as well as an ever-expanding material database is included for evaluating the optimal results.

Starting a project for a specific motor topology, MagOpt tries to find an optimal configuration for the given parameterized model considering the chosen objectives and constraints. During this optimization process (see Fig. 2), all needed simulation tools are automatically called by MagOpt. For electric machines, this can, e.g., range from the drawing of the motor geometry with a corresponding winding scheme to the particular electromagnetic simulation program.

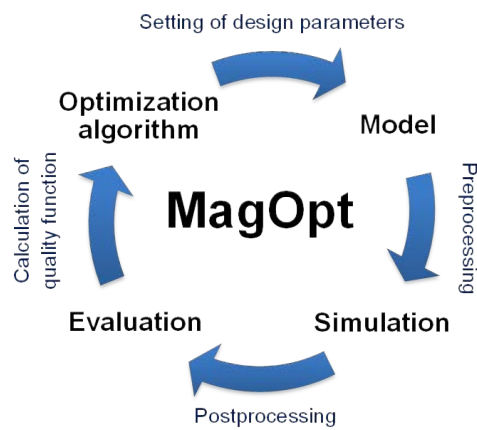


Figure 2. The MagOpt optimization process.

From the mechanical point of view, only rigid body calculations were carried out internally until now. Extensive mechanical simulations were conducted using external tools such as Pro/MECHANICA and the stand alone version of HOTINT.

The inclusion of a simulation program for rotor-dynamics is an inevitable next step for the efficient optimization of motor designs.

IV. OPTIMIZATION OF A ROTOR GEOMETRY

We consider the optimization of a rotor for several objectives such as energy efficiency, performance, durability and costs. In the optimization process, constraints regarding the size, weight, material types, maximum stresses and vibrational excitation have to be fulfilled for both applicability and safety regulations.

MagOpt uses genetic algorithms to acquire an optimal design starting from a user specified initial mechanical and electromagnetic setup of the rotor. In an optimization loop, MagOpt distributes numerous parallel subcalculations on a computer cluster.

HOTINT is one of these parallel executed tools, which receive a mechanical and electromagnetic configuration from the optimizer. It calculates relevant mechanical quantities necessary for the rating of the considered configuration.

In particular, HOTINT returns the maximum stresses due to centrifugal forces at operating speed.

Another characteristic indicator of the system is the eigenfrequency of the first bending mode. This frequency has to be considerably different from the operating frequency of the rotor. Ideally, this frequency is higher than the operating frequency to avoid resonance during run-up.

After an adequate number of iterations a set of optimal configurations is identified.

V. COUPLING OF MAGOPT AND HOTINT

The geometry of the rotor is defined in a parameterized model of the cross section which can be changed by MagOpt during the optimization process. This 2D geometry together with informations concerning the materials and connections of the individual parts of the rotor are set by MagOpt in the phase "setting of design parameters", compare Fig. 2. "Preprocessing" and the simulation itself are then performed by HOTINT, compare Fig. 3.

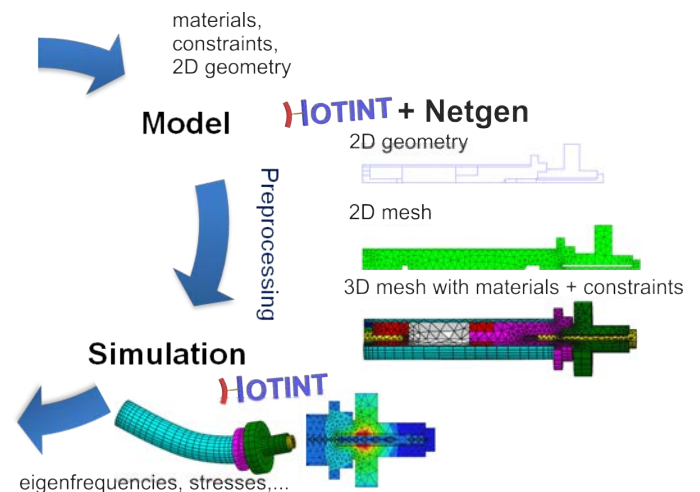


Figure 3. The coupling of MagOpt and HOTINT.

HOTINT is started from MagOpt with a single command including the path to an additional file in which a wide area of computational settings can be defined. These settings include the number of eigenfrequencies, coarsity of the mesh, path to the meshing tool, etc.

In order to avoid artificial numerical effects a symmetric mesh is required. Thus HOTINT generates a 3D mesh in a two step process from the provided cross section of the rotor. First HOTINT starts the open source meshing tool NETGEN [4] with appropriate settings to generate a 2D triangular mesh of the cross section.

The second step is to rotate this mesh in HOTINT to generate a symmetric 3D mesh: Depending on the number of points on the axis of rotation 3 different types of 3D finite elements are created when rotating a triangular mesh, see Fig. 4. If 2 points of the triangle are on the axis of rotation the resulting 3D object is a tetrahedral, 1 point leads to a pyramid and if no point is on the axis a prism is generated.

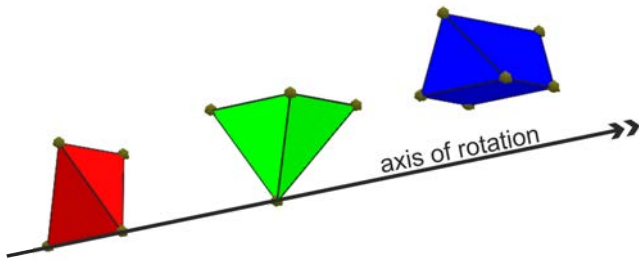


Figure 4. Rotation of a 2D triangular mesh leads to tetrahedrals, pyramids and prisms. Example for 3 triangles and a rotation angle of 45° .

The mesh is split into multiple meshes and the material data is set to represent the individual parts of the rotor. All joining surfaces between adjacent parts are cones, cylinders or discs with collocated nodes. Therefore joints with a node-node model are easy to implement and more complicated master-slave and node-surface models are not necessary if the relative motions are small. Corresponding to the specified connections of the individual parts of the rotor, the constraints are set automatically in HOTINT.

Depending on the settings either an eigenmode computation or a static FE computation is performed in the next step:

In the case of a static FE computation a centrifugal force due to the rotation of the rotor is applied to all elements of the mesh. The maximum value of the mises stress is then saved to an output file for MagOpt.

In the case of an eigenmode computation the number of free-free eigenmodes can be set as well as solver settings like the maximum number of iterations or an error bound. HOTINT uses the same mesh as described above to compute the eigenmodes and eigenfrequencies of the unsupported rotor. The lowest eigenfrequency corresponding to a bending eigenmode is the desired quantity for the rating of the current configuration in MagOpt. The eigenfrequencies are saved to an output file which is then read from MagOpt.

VI. NUMERICAL EXAMPLE OF A MECHATRONIC SYSTEM

The optimization of an electromagnetically levitated turbo charger is used in this work as example of a mechatronic system which shall be optimized. Different objectives for the optimization were defined by the involved branches of engineering:

- From the fluid mechanics point of view a large diameter of the wheel is advantageous because it leads to higher torques.
- Electro mechanics demand a large area and therefore length of the magnet in order to achieve a high efficiency.
- To avoid problems with the control, the first bending frequency of the rotor should be higher than the operating speed.
- Finally the stresses have to be sufficiently small to ensure a save and fatigue durable operation.

With respect to additional specifications the following 2 variables were defined to be changed by MagOpt: The diameter d of the wheel is varied between 15.5 and 60.0 mm and the length l of the magnet can be chosen between 15.0 and 60.0 mm, compare Fig. 5.

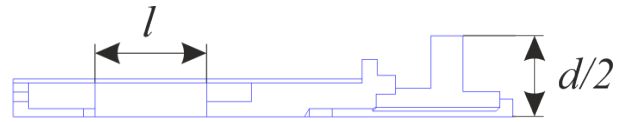


Figure 5. The diameter d of the wheel and the length l of the magnet are used as variables in the optimization.

Eigenfrequencies of the rotor and the stresses are obtained as results of the computations in HOTINT. As upper limit for the mises stress a value of $8e7 \text{ N/m}^2$ was chosen and the lowest eigenfrequency shall be maximized.

The result of the optimization with 4700 single computations is a pareto frontier as shown in Fig. 6.

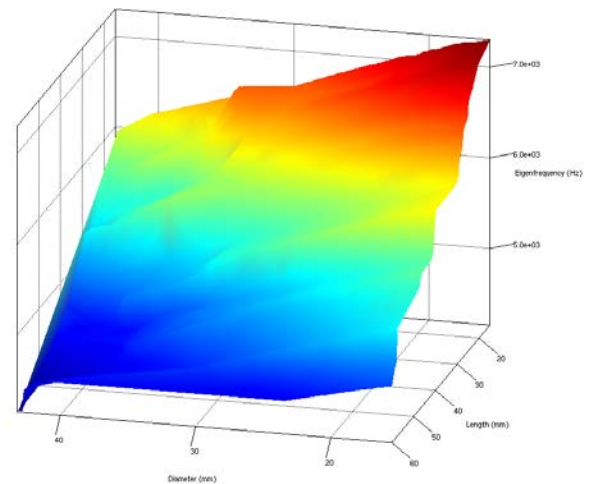


Figure 6. Pareto frontier as results of the optimization cycle: The lowest eigenfrequency as function of the diameter of the wheel and the length of the magnet.

VII. VALIDATION OF THE RESULTS

A prototype of the magnetically levitated high speed rotor was manufactured and the eigenfrequencies of this rotor have been measured.

Although strong simplifications concerning the interconnection of the individual parts of the rotor were made the results are very satisfying: In the manufactured prototype several parts are interconnected with force fits or glue. Parameters for these joints are hard to obtain and the evaluation of their influence on the eigenfrequencies was too time consuming for this first demonstrative work. All of these interconnections were modeled therefore as perfectly interconnected. The lowest bending frequency of the prototype obtained with HOTINT is 4620 Hz for a mesh with 5584 nodes. The measured eigenfrequency of the manufactured prototype is 3950 Hz.

Additionally the distribution of the mises stress due to the centrifugal force was computed with ANSYS with a much finer mesh with 46120 nodes. The results are shown in Fig. 7 for HOTINT and in Fig. 8 for ANSYS.

VIII. VERIFICATION BY ADDITIONAL SIMULATIONS

Before selecting one of the optimal configurations for producing a prototype additional simulations can be performed.

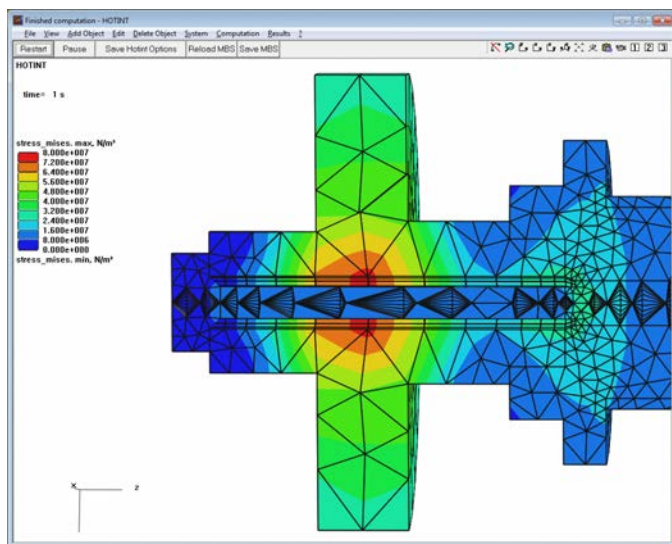


Figure 7. Results obtained with HOTINT: mises stress according to centrifugal forces due to a rotation with $f = 1$ kHz.

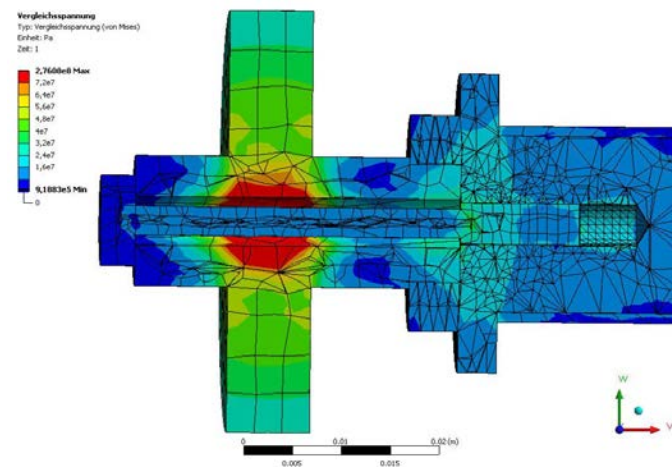


Figure 8. Results obtained with ANSYS: mises stress according to centrifugal forces due to a rotation with $f = 1$ kHz.

This is to verify the results of the optimization loop where certain assumptions have to be made to decrease computation time. The computation of the eigenfrequencies are made for the unsupported rotor as mentioned before. Neither eigenfrequency computation nor computation of centrifugal forces can include sliding or contact phenomena. A dynamic run-up simulation identifies the following effects:

- rigid body oscillations in the bearing
- frequency shift in the bending eigenmodes due to shrink-fit connections in the rotor
- sliding of shrink-fit connections
- loosening of glued joints

Using IO-elements we can test a controller design for the specific rotor in a virtual environment. Additionally the required driving torque can be determined in order to get through resonances. Through this preliminary evaluations the number of required prototypes can be minimized.

IX. ACKNOWLEDGMENT

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