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Simulation of an Explosive Resistant Flywheel Energy Storage Device Based on a Steel Strip Spiral

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Abstract
Flywheels have been proven as good and durable short-term energy storage devices. In this research, a numerical model of an explosive resistant flywheel in form of a glued spiral steel strip is presented and simulated. The model is set up parameterized to represent many design possibilities. These parameters are material parameters (Young's modulus and Poisson's ratio of steel as well as adhesive) and geometry parameters (number of turns, inner and outer diameters, and aspect ratio of steel and adhesive). The mechanical behavior of the flywheel was investigated. Six critical eigenfrequencies in the range of about 30 Hz to 90 Hz were identified. An additional contact model reveals that the detachment of the adhesive in only one spiral arm results in a complete breakdown of the structure. Hence, critical operational parameters of the flywheel are revealed, which is a major step toward reliable industrial development.

Keywords: Flywheel, energy storage, spiral, eigenfrequency, contact.

Introduction
Energy storage is gaining increasing interest due to the energy transition towards renewable energy sources. The future power grid will almost consist exclusively of instable and variable sources. Fluctuating power generation by renewable energy sources like solar and wind power, hydro power, biomass, and hydro power plants, biomass and particularly virtual power plants will increase [1–3]. Furthermore, the electro mobility will be predominate [4]. These fluctuations are very problematic for the power grid, as they destabilizing the frequency [3,5]. A grid consisting of mainly renewable energy sources needs additional frequency control devices in form of a short time energy storage [6,7].

Standard electrochemical storages like lithium-ion batteries are expensive, ecologically problematic and have a short lifetime based on their charging or discharging cycle. In addition, there is currently no economical recycling method for lithium-ion batteries and the mining of the required raw materials brings ecological and social challenges [8]. One way to stabilize the frequency of a power grid is by means of flywheels [7,9]. In this case, a heavy disc is set in rotation via a shaft using an electric motor. The kinetic energy is stored in it and can then be converted back into electrical energy (see Figure 1).

The advantages of flywheels are high cost efficiency, high lifetime of 20 years and longer with more than 20,000 full number of cycles, virtually maintenance free operation with easily replaceable components, nearly temperature independent performance, an unattainable volumetric storage density in comparison to other storage solutions and charging and discharging with very high power [10–14].

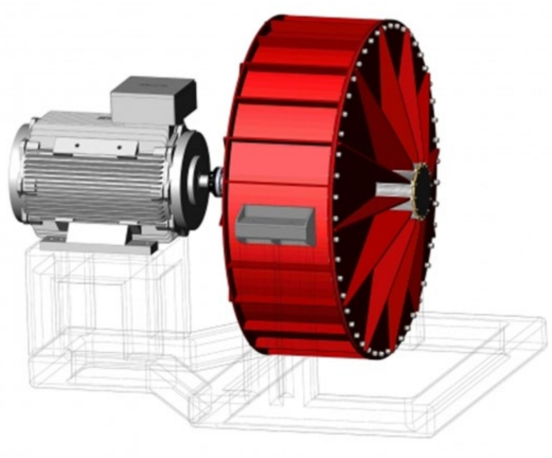

Figure 1: Structure of the flywheel energy storage system with housing and electric motor.

Current, flywheels are made of bulk material or carbon fiber reinforced plastic (carbon or CFRP) discs [15]. However, the large-scale use of state-of-the-art flywheels are slowed down due to the safety requirements. In case of a defect the energy stored in the flywheel will be released explosively [16]. There were repeated accidents in the past with great damage and personal injury with partly fatal outcome [16–20]. Thus, flywheels need an elaborate and expensive safety periphery, often provided by massive underground concrete structures.

To overcome these safety issues, an innovative new kind of flywheel is presented. The flywheel consists of a glued thin spiral steel strip with a thickness of about a quarter of a millimeter, which is coiled up on an aluminum core and centered by a shaft (see Figure 2).

Figure 2: Flywheel configuration with the spiral steel strip segment, the aluminum core, and shaft.

The shaft is then connected to an electric motor, which can also act as a generator. Here, in contrast to many other applications, steel has a clear advantage over carbon due to its high mass and hence the required rotational speed is considerably low, which makes complex and expensive bearing technology obsolete [21].

The complete flywheel is finally encapsulated by a compact steel housing. This housing is sufficient to protect the surrounding reliably. Further a sophisticated and expansive safety structure is unnecessary. In case of material failure, the steel strip spiral unreels and disintegrates which results in a smooth transition of the stored kinetic energy.

Figure 3: Disintegrated steel strip spiral without damage of the outer housing.

Figure 3 shows the confirmation of this mechanism by a preliminary experiment. Up to now, it was not possible to realize a stable functioning prototype, as the steel strip has already detached before reaching the maximum speed. The reasons for this behavior are still obscure and must be identified as part of this project to drive the market maturity of this storage technology forward and hence support the energy transition.

Material and methods

The COMSOL® Structural Mechanics module was used to perform an eigenfrequency and a contact study. The model was set up parameterized to represent all design possibilities. These parameters are material parameters (Young's modulus and Poisson's ratio of steel as well as adhesive) and geometry parameters (number of turns, inner and outer diameters, and aspect ratio of steel and adhesive). The flywheel consists of up to 100 turns, which poses a challenge for the creation of a numerical model due to the high aspect ratio.

Geometry development

The complete model is generated by a JAVA method using the so-called "Application Programming Interface", since a manual selection is no longer practicable due to a high number of domains. The model is implemented as 2D- and 3D-geometry and the adhesive is explicitly represented as a domain. According to the current state of knowledge, a simplification of these assumptions is no longer possible, since

1. the adhesive must be present as a domain to keep track of the stress states within the adhesive layer.

2. no symmetries exist. Axial symmetry does not exist due to the "break in symmetry" of the spiral in comparison to circular segments.

Based on the current design approach, the coils start at a radius of 0.4 m and end at 0.7 m. The thickness of the steel strip and that of the adhesive layer have an aspect ratio of about 10:1. The geometry is illustrated in Figure 4.

A linear elastic material with the following material data has been assumed as a first approximation for the model (see Table 1).

Table 1: Material parameters for the linear elastic model

	Young´s Modulus [GPa]	**Poisson´s ratio [1]**	**Thickness [kg/m³]**
Steel	190	0.3	7800
Adhesive	5	0.3	1200

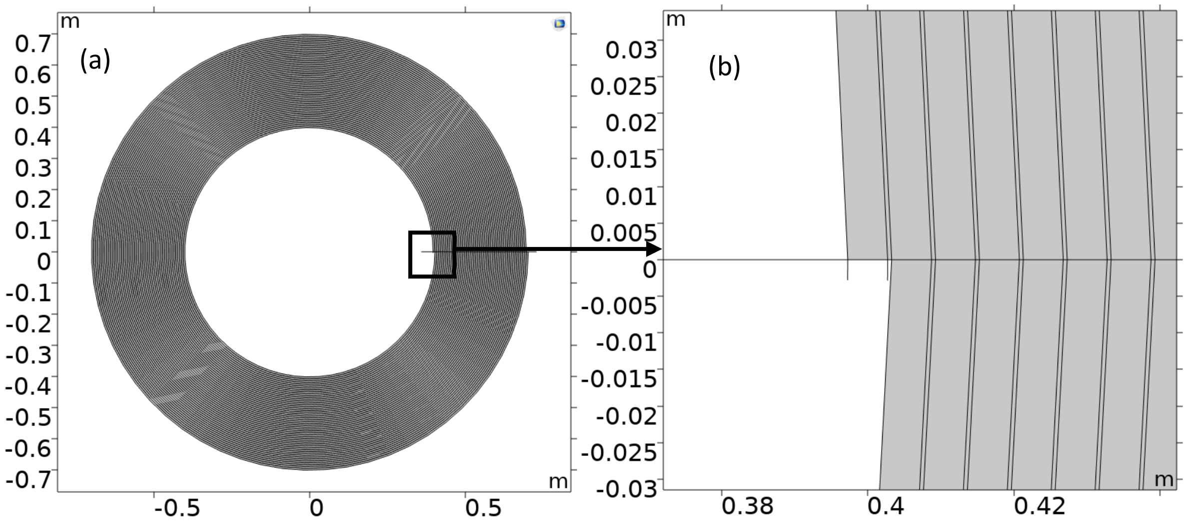

Figure 4: Geometry of the flywheel. (a) shows the complete geometry and (b) a magnification of the „start winding". The steel strip and the adhesive have an aspect ratio of 10:1.

Mesh

For the domain of the inner aluminum core a quad swept mesh is used. For the domains of the outer spiral arms a hexaeder mesh with a finer resolution is used as shown in Figure 5. It should be mentioned that a refinement is applied to four inner spiral windings exclusively for the contact model.

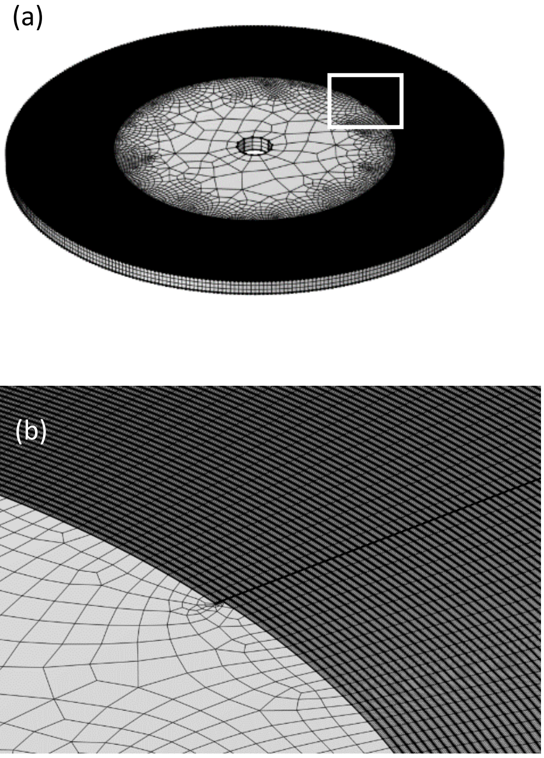

Figure 5: (a) Mesh of the flywheel. (b) Zoom of the white rectangle area.

Results of the eigenfrequency study

The mechanical behavior of the flywheel was investigated for different design possibilities. The simulation results show six critical eigenfrequencies in the specified range of 0 to 5500 rpm. The six resulting eigenfrequencies for the flywheel with 100 spiral turns are shown in Table 2.

Table 2: Eigenfrequencies

No.	Eigenfrequencies
1	37.3 Hz
2	37.3 Hz
3	56.8 Hz
4	70.4 Hz
5	76.1 Hz
6	76.1 Hz

It is worth to mentioning that eigenfrequencies 1 and 2 as well as 5 and 6 are respectively virtually identical, thus resulting in nearly identical mode shapes. Eigenfrequencies 3 and 4 are radial shaped and similar with the exception, that eigenfrequency 3 has an additional deformation in axial direction. All corresponding eigenmodes of the flywheel with 100 spiral turns are shown in Figures 6-9.

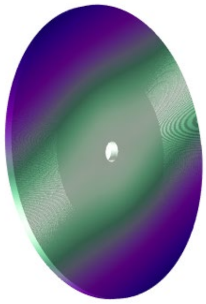

Figure 6: Eigenmode that corresponds to an eigenfrequency at 37.3 Hz*.*

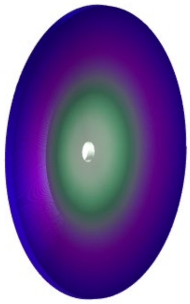

Figure 7: Eigenmode that corresponds to an eigenfrequency at 56.8 Hz*.*

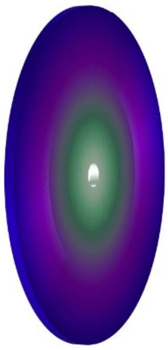

Figure 8: Eigenmode that corresponds to an eigenfrequency at 70.4 Hz*.*

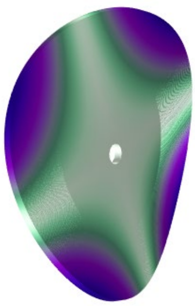

Figure 9: Eigenmode that corresponds to an eigenfrequency at 76.1 Hz*.*

Results of the contact study

In case of resonance at one of the frequencies found in the previous chapter a spiral winding detachment of the flywheel caused by adhesive failure could occur. This is especially the case if shear forces are present. Figure 10 shows the result of such a scenario.

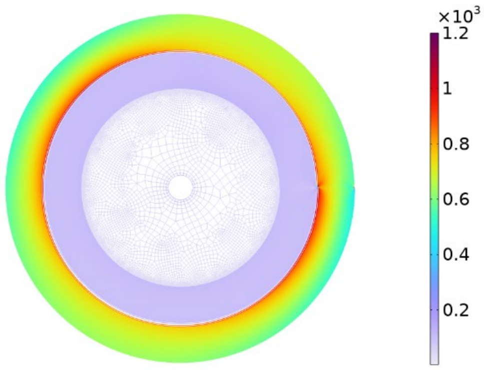

*Figure 10: Von Mises stress (*MPa*) of the flywheel contact model at a rotation of* 5000 rpm*.*

Here, one adhesive winding is removed from the middle of the spiral. This enhances the stress in the surrounding area significantly. The magnitude of the stress exceeds 1.2 GPa and thus is above the critical stress of most high quality steels. It is noted, that artefacted numerical peak values at the edges of the strip were removed. It is likely that adjacent windings can not withstand the acting forces. Thus, a complete disintegration of the entire structure is predicted as it is observed in the experiment.

Conclusion

In this project, a numerical model of an explosive resistant flywheel was developed and analyzed. The key question was to identify the mechanism of the failure during operation due to detachment of the spiral steel strip. The mechanical behavior of the flywheel was investigated for different design possibilities. Therefore, eigenfrequency as well as contact studies were performed. Six critical frequencies could be identified within the operating range. In case of resonance at one of these frequencies a detachment of one inner single spiral could occur. The acting forces are then exceeding the tensile stress of high strength steel and tear up the loose steel strip. This could lead to breakdown of the entire flywheel. Knowledge from these numerical simulations will be used to improve the manufacture of prototypes in the future.

References

[1] S. Weitemeyer, D. Kleinhans, T. Vogt, C. Agert, *Integration of Renewable Energy Sources in future power systems: The role of storage.* Renewable Energy, vol. 75, pp. 14-20, 2015.

[2] M.I. Alizadeh, M. Parsa Moghaddam, N. Amjady, P. Siano, M.K. Sheikh-El-Eslami, *Flexibility in future power systems with high renewable penetration: A review.* Renewable and Sustainable Energy Reviews, vol. 57, pp. 1186-1193, 2016.

[3] M. Liserre, T. Sauter, J. Hung, *Future energy systems: integrating renewable energy source into the smart power grid through industrial electronics.* IEEE Industrial Electronics Magazine 4, pp. 18-37, 2010.

[4] K. Steinbacher, S. Röhrkasten, *An outlook on Germany's international energy transition policy in the years to come: Solid foundations and new challenges.* Energy Research & Social Science, vol. 49, pp. 204-208, 2019.

[5] A. Keyhani, *Design of Smart Power Grid Renewable Energy Systems.* 3rd ed., John Wiley & Sons, Inc., Hoboken, New Jersey, 2019.

[6] K.M. Tan, T.S. Babu, V.K. Ramachandaramurthy, P. Kasinathan, S.G. Solanki, S.K. Raveendran, *Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration*. Journal of Energy Storage, vol. 39, p. 102591, 2021.

[7] R. Takahashi, J. Tamura, *Frequency Stabilization of Small Power System with Wind Farm by Using Flywheel Energy Storage System.* IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, Cracow, Poland, 2007.

[8] Y. Wang, N. An, L. Wen, L. Wang, X. Jiang, F. Hou, Y. Yin, J. Liang, *Recent progress on the recycling technology of Li-ion batteries.* Journal of Energy Chemistry, vol. 55, pp. 391-419, 2021.

[9] M.L. Lazarewicz, A. Rojas, *Grid frequency regulation by recycling electrical energy in flywheels.* IEEE Power Engineering Society General Meeting, vol. 2, pp. 2038–2042, 2004.

[10] M. Amiryar, K. Pullen, *A Review of Flywheel Energy Storage System Technologies and Their Applications.* Applied Sciences 7, no. 3, pp. 286-296, 2017.

[11] J.G. Bitterly, *Flywheel technology: past, present, and 21st century projects.* IEEE Aerospace and Electronic Systems Magazine, vol. 13, pp. 13-16, 1998.

[12] Z. Long, Q. Zhiping, *Review of Flywheel Energy Storage System.* Proceedings of ISES World Congress 2007, vol. I-V, pp. 2815-2819, 2007.

[13] R. Peña-Alzola, R. Sebastián, J. Quesada, A. Colmenar, *Review of Flywheel based Energy Storage Systems.* Proceedings of the 2011 International Conference on Power Engineering, Energy and Electrical Drives, pp. 1-6, 2011.

[14] R. Sebastián, R. Peña Alzola, *Flywheel energy storage systems: Review and simulation for an isolated wind power system.* Renewable and Sustainable Energy Reviews, vol. 16, no. 9, pp. 6803-6813, 2012.

[15] I. Hadjipaschalis, A. Poullikkas, V. Efthimiou, *Overview of current and future energy storage technologies for electric power applications.* Renewable and Sustainable Energy Reviews, vol. 13, no. 6-7, pp. 1513-1522, 2009.

[16] R. vor dem Esche, *Safety of Flywheel Storage Systems.* Stornetic GmbH, White Paper, 2016.

[17] D. Bender, *Recommended Practices for the Safe Design and Operation of Flywheels.* Sandia National Laboratories, Albuquerque, New Mexico; Livermore, California, U.S.A, Report: SAND2015-10759, 2015.

[18] L. Jiang, W. Zhang, G.J. Ma, C.W. Wu, *Shape optimization of energy storage flywheel rotor.* Structural and Multidisciplinary Optimization, vol. 55, no. 2, pp.739-750, 2017.

[19] E.T. Duran, A.Ç. Sever, *Dynamic Simulation and Endurance Limit Safety Factor Calculation for Crankshaft - Comparison of Single Mass and Dual Mass Flywheel.* Society of Automotive Engineers, SAE Technical Paper 208-01-2622, 2008.

[20] A.P. Coppa, *Flywheel Containment and Safety Considerations.* An Assessment of Integrated Flywheel System Technology, NASA-CP 2346, pp. 243-264, 1984.

[21] A.V. Filatov, E.H. Maslen, *Passive magnetic bearing for flywheel energy storage systems.* IEEE Transactions on Magnetics, vol. 37, no. 6, pp. 3913-3924, 2001.

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