Design Optimization of Flywheel Energy Storage System Rotor for Wind Power Smoothing

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Abstract:

This project studied flywheel rotor design for high speed flywheel energy storage systems. A two-dimensional plane stress finite element model was developed to predict radial and hoop stress distributions in a flywheel rotor under high centrifugal loads. The FEA model was used to study the effects of multi-ring configuration and hub design on the distribution of radial and hoop stress distributions. It was found that a multi-ring design with gradual increase of stiffness in the radial direction can reduce the radial tensile stress and thus reduces the risk of delamination. A flexible hub design was found to reduce hoop and radial stresses in the shaft and radial stress in reduction of radial stress in the rotor.

Introduction:

The growth of energy consumption and environmental considerations have driven the recent advances in application of renewable energies such as solar and wind turbine units. Power fluctuations of wind turbines may markedly affect power quality in power grids, especially in weak or isolated grids. These energy fluctuations can be effectively managed with the help of the energy storage devices. Flywheel Energy Storage Systems (FESS) are electromechanical batteries which provide effective energy storage and thus smooth wind power variations.

Several advantages are associated with the use of FES systems compared to electrochemical batteries. FES systems offer superior energy discharge rates than comparable electrochemical batteries, which makes FES systems attractive for power smoothing. They can operate at a much wider temperature range and are not subject to many of the common failures of chemical rechargeable batteries. They are also less potentially damaging to the environment, being largely made of inert or benign materials. The specific power of many FES systems ranges between 5 and 10 kW/kg whereas values for electrochemical batteries are typically smaller by magnitude. The specific energy of advanced FES systems may exceed 200 Wh/kg. Compared to lead-acid battery systems, an up to eight times higher purchase cost per amount of energy stored can be expected for FES systems. However, the considerably higher price of FES systems is offset by their significant longer life, which may exceed that of electrochemical batteries by the same factor. Chemical batteries cannot withstand the power pattern variations and suffer badly due to charging and discharging. Cost consideration also must include the storage system's energy recovery efficiency.

Flywheel Energy Storage System

Figure 1 shows a high speed flywheel energy storage system for wind power energy storage. A flywheel energy storage system mainly consists of a flywheel rotor, magnetic bearings, a motor/generator, a vacuum chamber, and power conversion system. Flywheel energy storage systems (FESS) are electromechanical systems that store kinetic energy and regenerate electricity through coupled flywheels and electric machines. For high wind power levels, part of wind power energy is stored in the flywheel and the electric machine works as a motor to accelerate the flywheel. During low power levels, the stored kinetic energy is used to drive the electric machine and regenerate electricity to be delivered to the grid. Magnetic bearings and vacuum chamber are used to minimize frictional losses that occur in bearings and with the air surrounding the rotating components.

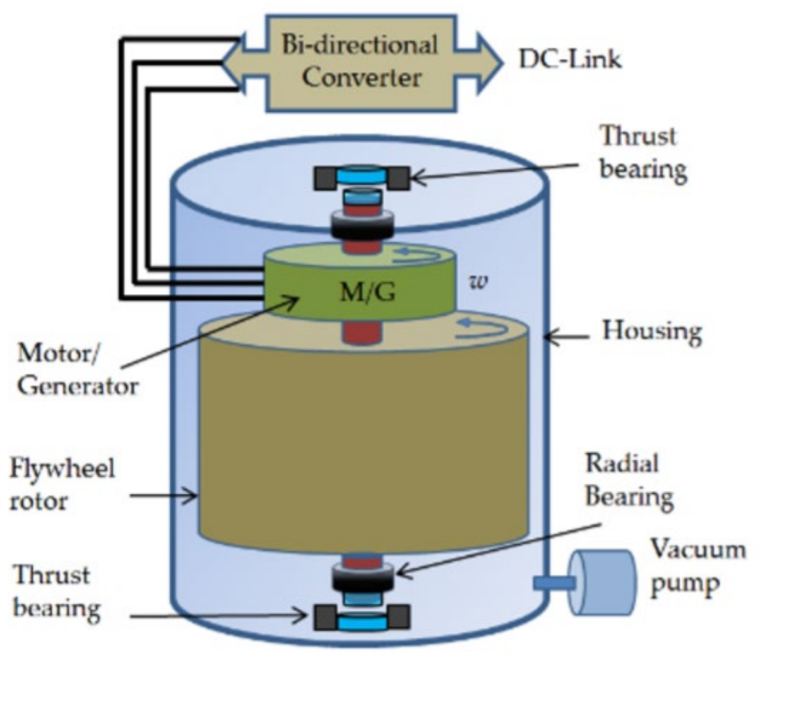

Fig 1: FESS Schematic [1]

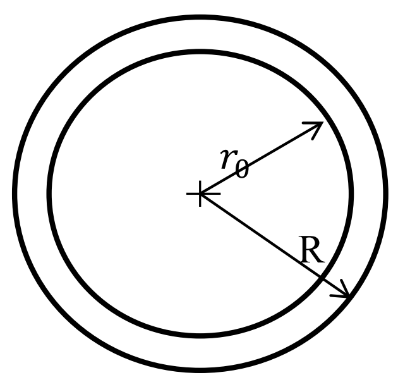

Fig 2: Flywheel rotor

Flywheel Rotor Design and Optimization

Energy stored in the flywheel is given by the eq. (1). The kinetic energy storage equation is governed by the angular speed, ω, and mass moment of inertia I, of the flywheel.

$$E = \frac{1}{2} I\omega^2 = \frac{1}{2}\rho\pi h(R^2 - r_o^2)I\omega^2 \qquad (1)$$

$$R\omega_{max} = \sqrt{\frac{\sigma_\theta}{\rho}} \qquad (2)$$

The maximum allowable angular velocity, ω_{max}, is under the mechanical strength of the rotor material and the rotor geometry as shown in eq. (2). The flywheel rotor is considered as a thin rim of inner and outer diameters r_o, R and thickness h. Eq. (2) also shows that a material of high hoop strength, σ_θ, and low density, ρ, is desirable for achieving a high angular velocity. Thus, low density, high strength fiber reinforced polymer composite materials with filament wound in circumferential direction are often used in high speed flywheel rotors. The design of flywheel rotor needs to consider many factors, such as the stored energy, mass, cost, materials, cross sectional geometry, thickness, operational speed, hub design, etc.

Analytical Model and Finite Element Model

The analytical radial and hoop stress distributions in a free rotating thin rim as shown in Fig. 1 can be calculated with eqs. (3) and (4). The material is assumed to be isotropic.

$$\sigma_r = \frac{3+\upsilon}{8}\rho\omega^2\left[{r_0}^2 + R^2 - \left(\frac{Rr_0}{r}\right)^2 - r^2\right] \qquad (3)$$

$$\sigma_\theta = \frac{3+\upsilon}{8}\rho\omega^2\left[{r_0}^2 + R^2 + \left(\frac{Rr_0}{r}\right)^2 - \frac{1+3\upsilon}{3+\upsilon}r^2\right] \qquad (4)$$

The static structural model of the free rotating ring under centrifugal force is considered as a 2D plane stress finite element model. Taking advantage of symmetry, a section of the 2D ring, as shown in Fig. 3, is modeled to reduce mesh count. Symmetric boundary constraints are imposed at the lateral faces. Quadratic quadrilateral elements are used in the simulation od 2D plane stress solids.

FEA simulation of a steel ring was simulated in ANSYS 19.1. The sting ring has outer radius of 0.17 m and inner radius of 0.09m and a thickness of 0.3 m. This model was given rotational velocity of 10000 rpm. The material properties of steel is listed in Table 1. The radial and hoop stress distributions in the ring are shown in the contour plots in Figs. 4 and 5. The maximum hoop stress is at the inner surface and maximum radial stress is inside the ring. Hoop stress is found to be much higher than the analytical stress. The FEA results are found to match the analytical results as shown in Fig. 6.

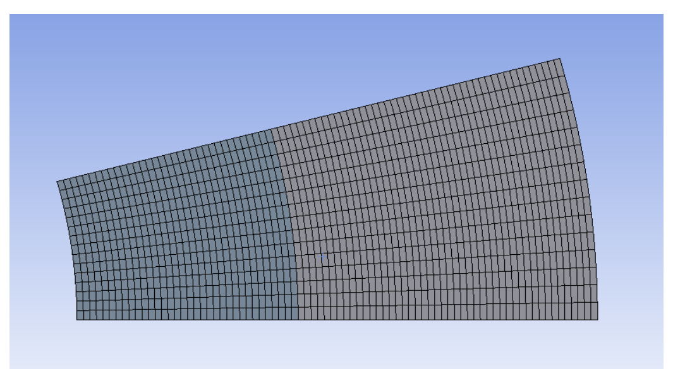

Fig 3: Meshing of a steel ring

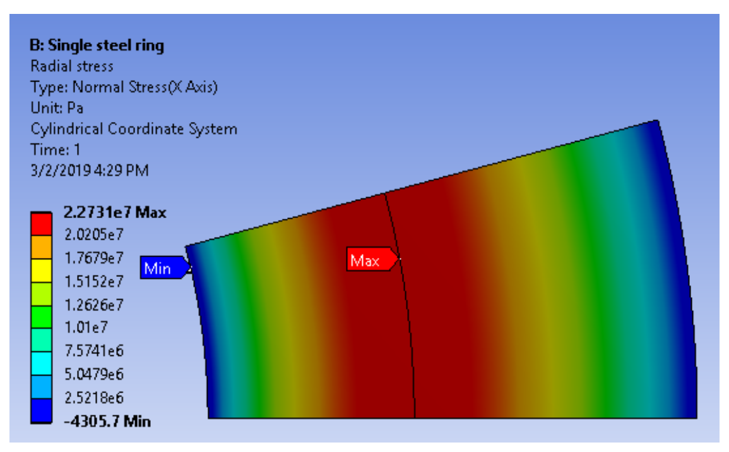

Fig 4: Radial Stress of steel ring

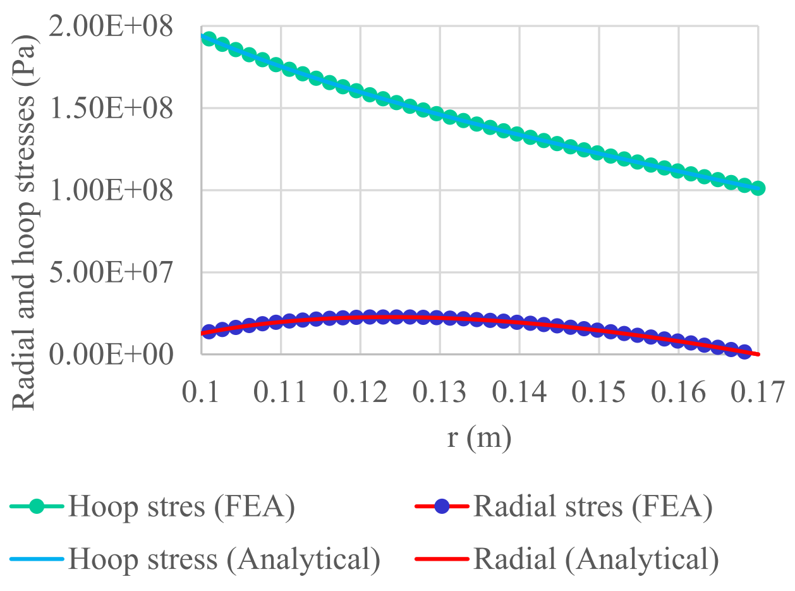

Fig 6: Comparison of FEA and analytical results

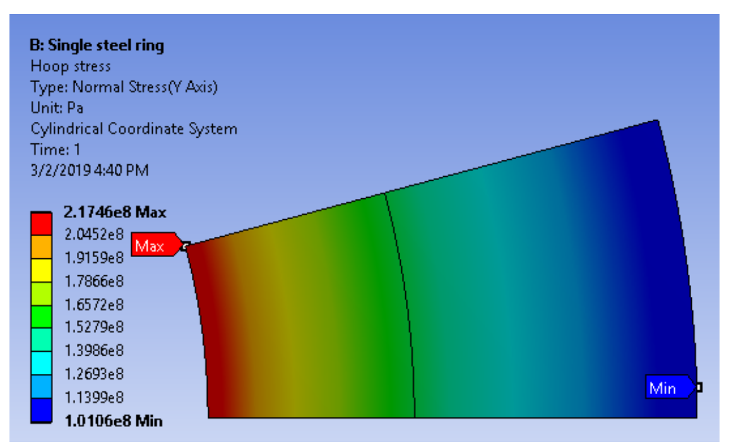

Fig 5: Hoop Stress of steel ring

Table 1: Material Properties [2]

Property	Density (kg/m³)	Poisson's Ratio	Young's Modulus (GPa)	Tensile strength (MPa)	Compressive strength (MPa)
Structural Steel	7850	0.3	200	460	250
Aluminum	2600	0.3	68.9	310	280
T7000 Epoxy	1600	0.3	138/9	2940/25	1600/168
E-glass Epoxy	1800	0.28	38.6/8.27	1062/25	610/118

FEA Simulation of Flywheel Rotor

Fiber reinforced composite flywheels are found to fail as delamination in the polymer matrix in radial direction as well as fiber breakage in hoop direction. Stress distributions in a flywheel rotor of composite materials are different from those predicted by the analytical model due to the anisotropic properties of composite materials and the connection with a hub. Fiber reinforced plastic composite materials have much higher stiffness and strength in the circumferential direction than in the radial direction. Flywheel rotor design requires integration of the rotor geometry optimization with material selection and hub design.

This project studied the multi-ring design of a rotor with flexible and stiff hubs using above validated FEA model. Hoop direction properties of two composite materials listed in Table 1 are used for the multi-ring rotors. The steel shaft has a radius of 0.02m. This model was given a rotational velocity of 40000 rpm.

Single Ring and Multi-ring Rotors

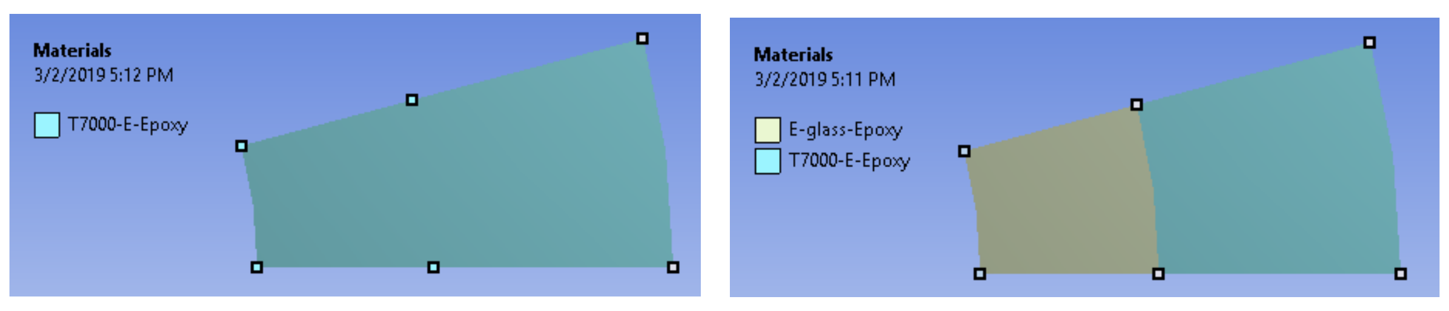

Fig 7: Single ring (left) rotor and multi-ring rotor (right)

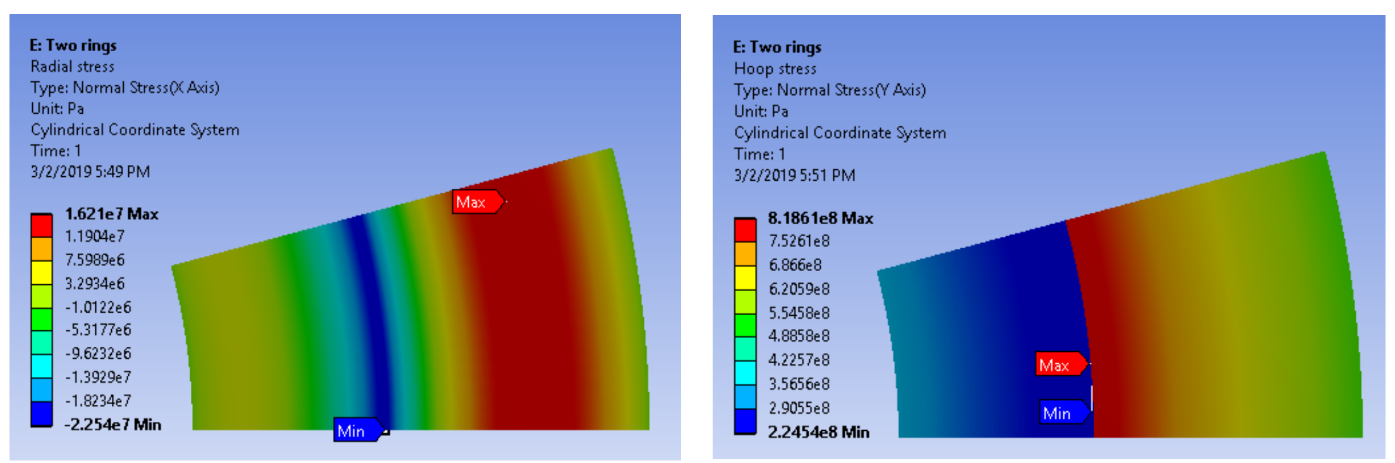

Fig 8: Stress in a two-ring rotor: radial (left) and hoop (right)

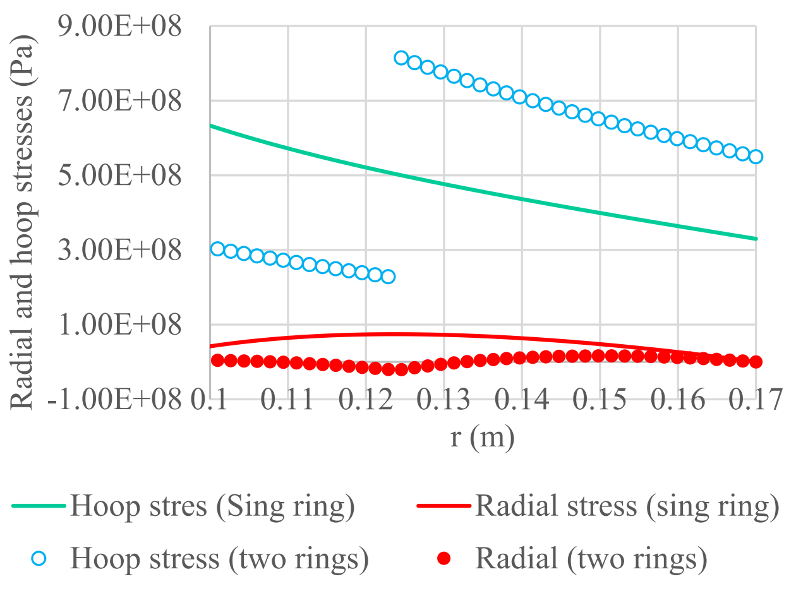

Fig 9: Comparison stresses distributions in a single ring rotor and a multi-ring rotor

As it seen in Fig. 7, the single ring rotor is made of a T7000 epoxy and the multi-ring rotor has two rings with the inner ring of E-glass epoxy and the outer ring of T7000 epoxy. T7000 epoxy has higher stiffness and strength than E-glass epoxy. The higher stiffness in the second ring redistributed the radial stresses in both rings. Hoop stress is reduced in the first ring and radial stresses are reduced in both rings.

Multi-Ring Rotor with Flexible and Stiff Hubs

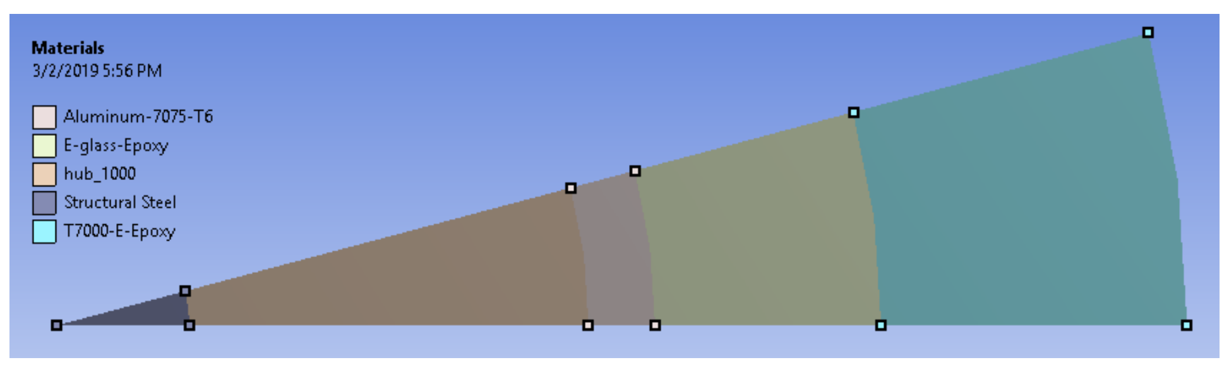

Fig 10: Multi-ring rotor with shaft and hub assembly

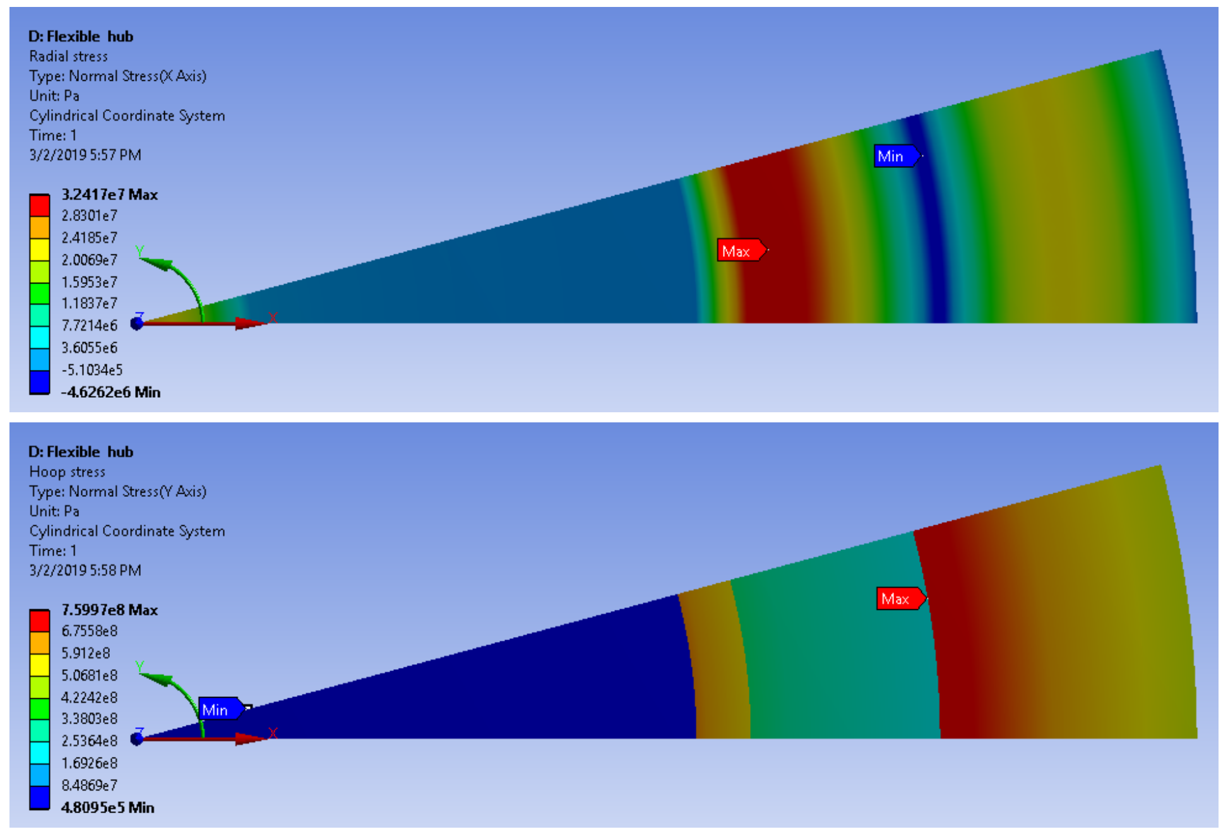

Fig 11: Radial stress (top) and hoop stress (bottom) with a flexible hub

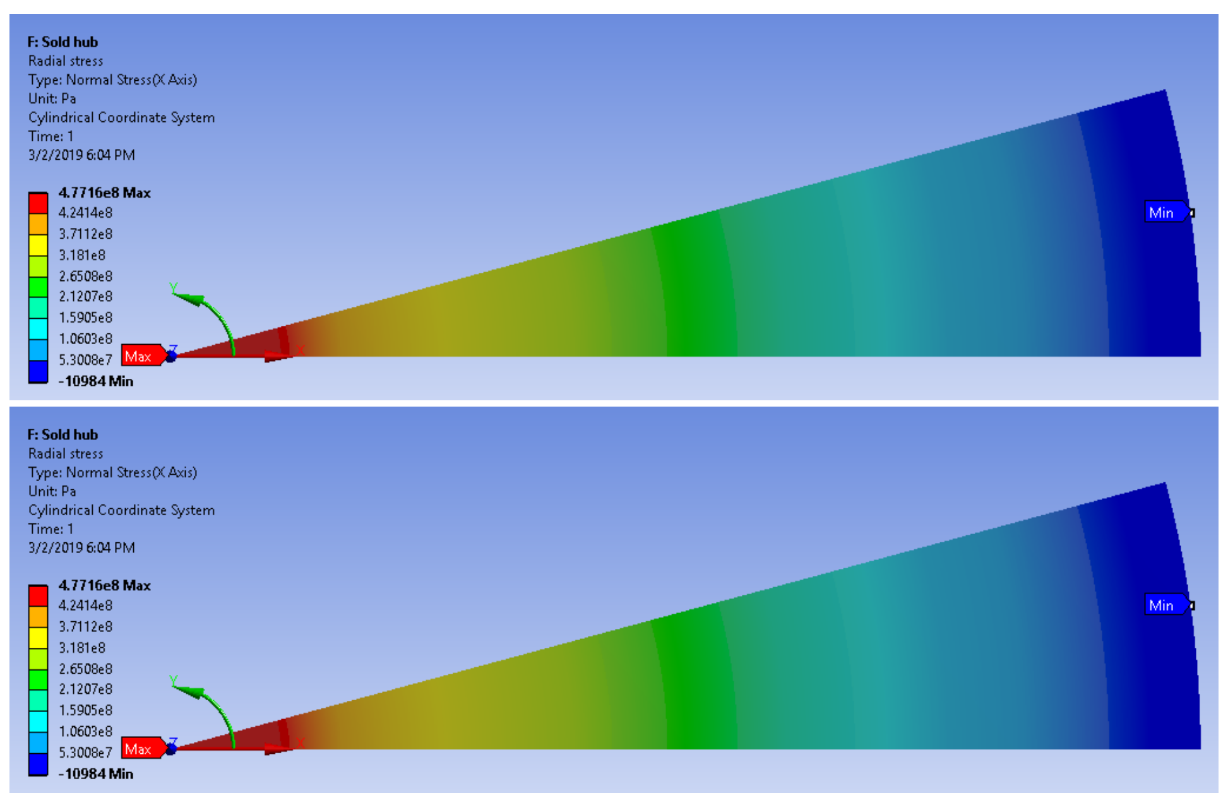

Fig 12: Radial stress (top) and hoop stress (bottom) with a solid hub

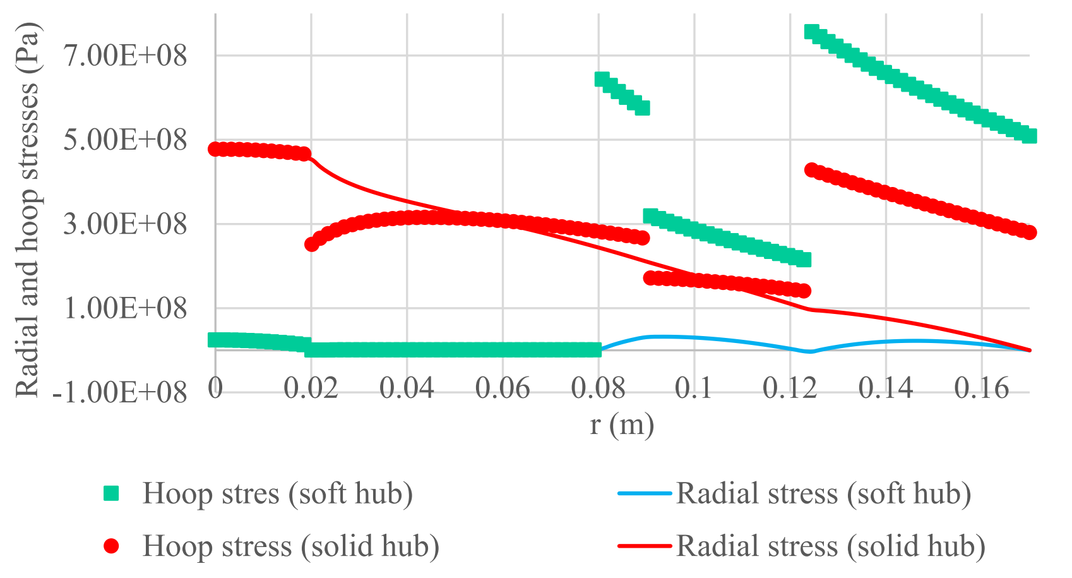

Fig 13: Comparison of stresses with a flexible and solid stiff hub

Fig. 10 shows an assembly of steel shaft, aluminum hub, and two rings rotor The flexible hub is modeled as two rings with the inner section modeled as a weak material and a thin solid ring connected with the rotor. The stiff hub is modeled as a solid aluminum ring. As shown in Fig. 13, a very stiff hub results in high stresses in the shaft, hubs and lower stresses in the rotor. A flexible hub significantly reduces stresses in the shaft and hubs and also the radial stress in the rotor rings, as shown in Fig. 12. It also increases the hoop stresses in the rotors which has been considered in the high strength materials in the rotor.

Conclusions and Future Work:

This poster has presented a FEA model to predict the radial and hoop stresses distributions in a multi-ring flywheel rotor with shaft and hub assembly. This model will be used to optimize flywheel rotor and hub design with composite materials to achieve optimal energy storage capacity at low cost for FESS. This model will further been developed to include composite anisotropic properties, press-fitting between rings, and failure criteria. A three-dimensional model will also be developed to study the detailed hub design.

References :

[1] M. E. Amiryar, K. R. Pullen, A review of flywheel energy storage system technologies and their applications, *MDPI* (2017)

[2] S. K. Ha and M. H. Kim, S. C. Han and T.-H. Sung, Design and spin test of a hybrid composite flywheel rotor with a split type hub, Journal of Composite Materials, Vol. 40 p 2113-2130, 2006.