Simulation of an Electromagnetic Spring using EMS Software

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***Abstract*—In this paper we present the design and simulation of an electromagnetic spring using EMS software. The proposed electromagnetic spring is used as a variable stiffness actuator for robotic gripper applications. First we will present the mechanical design of the compliant actuator and the working concept. Then we will present results from EMS simulation software provided by EMWorks to verify the features of the proposed spring. Finally we will discuss the cooling techniques that we propose to use for this actuator.**

I. Introduction

In recent years, many researchers have incorporated a compliant element in the design of robotic actuators. Series Elastic Actuators (SEA), shown in Fig. 1, are compliant actuators that have a passive compliant element, such as a mechanical spring, between a high gear ratio motor and the environment [1]. Having such compliant element creates a buffer between the actuator and the environment, enabling the actuator to effectively absorb shocks and store energy. Moreover, the compliant element will turn the force control problem into a position control problem by using the spring as a force sensor.

Traditional SEAs suffer from lack of versatility when it comes to the stiffness of the compliant element. Having a spring with fixed stiffness presents an optimization problem based on the intended task of the actuator (CITE). One way to solve this engineering trade-off is to use nonlinear springs [2] [3]. Nonlinear springs can exhibit the properties of both soft and stiff springs. For stiffening nonlinear springs, the spring will exhibit a low stiffness at low deflections for accurate force control and increased bandwidth for higher deflection. Nonlinear springs also have the ability to store more energy and absorb shocks. Despite these benefits, the use of SEAs with nonlinear springs suffers from it's in ability to change the stiffness curve. This means that the stiffness of the spring is always coupled to the deflection of the spring.

A solution for this is the use of variable stiffness actuators, where the stiffness can be tuned through a secondary input such as another motor [4] [5] . However, most VSA's are mechanically bulky and complicated, for most of these proposed VSAs the stiffness change is sometimes slow. This research proposes a nonlinear magnetic spring that exihibits stiffening characteristic and has the capability to increase or decrease it's stiffness profile through an electro magnetic coil. The change of the stiffness in the electromagnetic spring happens in a very short time compared to mechanically changing the stiffness in an actuator through pivot method.

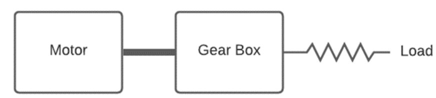


Fig. 1: Series Elastic Actuator

In this paper we show the proposed electromagnetic variable stiffness as well as its simulation using EMS [6] software provided by EMWorks Inc.

II. Mechanical Design

The electromagnetic spring proposed here is comprised of an active permanent magnet (PM) between two stationary permanent magnets. The moving magnet is floating between the two stationary magnets and is in repulsion with both stationary magnets as shown in Fig. 2. All three PMs are encapsulated with a magnetic coil. Upon changing the current in the coil, the stiffness of the spring can be increased or decreased. This means that the spring will have an inherent stiffness at zero current, but will be able to change the stiffness if needed by applying a current to the coil.

A. CAD Model for EMS Simulation

To study the spring characteristics such as the force-displacement curves, we simplified the model to the one shown in 2. The simplified CAD model is reduced to just the two stationary PMs, one moving magnet, one coil as well as the Air geometry necessary for the EMS simulation. Since we are performing static EMS studies to simulate forces on the moving magnet, reducing the model to this basic form would reduce the complexity of the model as well as the amount of interference between parts that need to be resolved in Solidworks.

III. Simulation

For this white-paper, we performed a static EMS study as well as a steady state thermal analysis of the actuator. For our

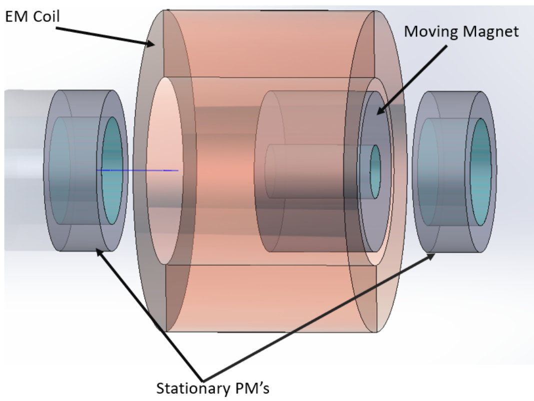


Fig. 2: Solidworks model showing the Electromagnetic Spring with the specified air boxes

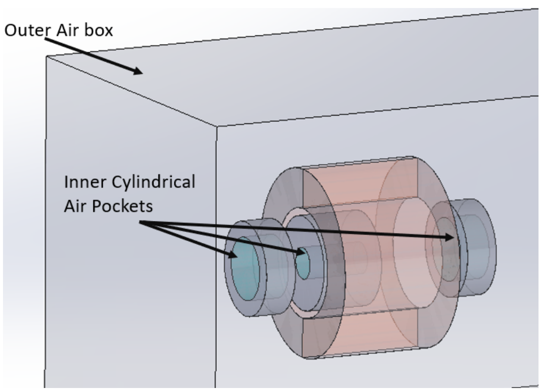


Fig. 3: Solidworks model showing the Electromagnetic Spring with the specified air boxes

first study using EMS, our aim was to simulate the force profile for the spring as we change the current. In order to evaluate that, we perform a parametric study, which entails varying both the position of the moving magnet as well as current. The current values are varied between [-8 Amp, 8 Amp] with a step of 1 Amp. For each current value, the deflection of the moving spring X as shown in Fig. 5 is varied from [0.01 0.99] in. It is important to note here that the equilibrium point, where the magnet experiences zero force is at $X = 0.5$in. For the second study performed, we evaluated the viability of cooling the spring under still air as well as water. For this study, a parametric variation is also used were the moving magnet is kept at the equilibrium position of $X = 0.5in$ and the current was varied with a 1Amp step.

A. Geometry and meshing

The geometry of the study has been reduced to the form shown in the 3. Since we are performing static analysis to simulate the force at the moving magnet, components that do not contribute to these forces were eliminated. This will make the simulation simpler. Also reducing the CAD model to only necessary components for the study will reduce the amount of interference between parts in the assembly. And since it is a

Fig. 4: Actual coil used for the proposed spring

requirement of EMS to eliminate all interference reducing the number of components will reduce the number of interference that needs to be dealt with.

Since EMS also requires an Air box to encapsulate all components, the cavity feature in Solidworks needs to be used in order to remove any material overlap. For some instances, this simply doesn't resolve the interference, especially for annular shapes as is the case for the PMs. Multiple ways were explored in order to resolve this issue such as increasing the size of the cavity by a small percentage. However, The way that proved most useful is when we included cylindrical air pockets as separate parts inside the stationary and moving magnets. Then we would apply the cavity features to the surrounding air box and include these added Air pockets in the subtraction process.

B. Simulation setup

1) Material Setup: The materials used in our spring are as follows, all magnets are N52 neodymium magnets. The coil is made from copper winding's.

TABLE I: PM and Coil Geometries

Property	Outer D (in)	Inner D (in)	length (in)
$Active\ PM$	0.75	0.25	0.5
$Inactive\ PM$	0.75	0.5	0.25
$Coil$	0.875	0.25	1

The coercivity of the magnets is set up such that the moving magnet is in repulsion with both stationary magnets as shown in 5. The coil parameters in the simulation are based on the actual coil we used in our spring shown in Fig. 4. The number of turns assigned to the coil were estimated based on the measured resistance of the coil itself. Using the Resistance of the coil being 5.3 Ω wire and the provided resistance per meter of the 24 AWG wire which is 0.0842 Ω/m, we estimated the number of turn to be around 600 turns.

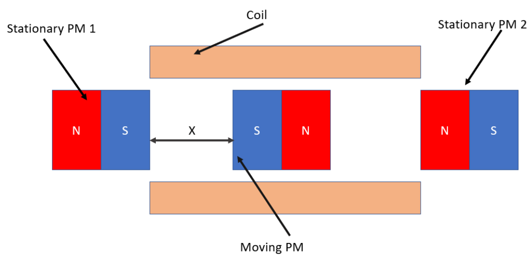


Fig. 5: Cross Section of Spring showing the coercivity direction of the magnets used

2) Mesh and Mesh Control: Since the simulation involves a large number of scenarios, we tried to minimize the time of each simulation as well as get as much of an accurate results from the simulation. For the first study, a mesh value of 0.1in was applied to all components, however since we are simulating the force on the moving magnet, a mesh control of 0.02in was applied to it. We found that beyond 0.02in for the moving magnet the results did not improve significantly.

For the second study involving thermal steady state, the mesh was kept at 0.1in overall. As the steady state temperature does not need to be extremely accurate.

IV. Results

In order to estimate the variation in force and stiffness of the designed spring, we plotted the simulated force against the active magnet displacement. Fig. 6 shows how the force on the moving magnet varies as the active magnet is displaced from the equilibrium position. The active magnet displacement ranges from [-0.5, 0.5]in which is the range of the spring. A displacement of 0in is when the magnet is exactly in the middle of the spring and corresponds to a value of X = 0.5in from 5. The force vs displacement on the moving magnet is plotted for each current value.

We also used EMS to simulate the core temperature of the spring when cooled through flowing water and still air. Cooling through still air had proven very ineffective, giving a very high steady state temperature. If only still air is used, the temperature of the spring will reach the maximum allowed for the provided winding which is 200°C at about 2 Amps. However, water cooling proved much more effective as the spring can remain within operating temperature even at very high current. Fig. 7 shows the variation in the steady state core temperature of the spring as a function of current through the coil.

Sample simulation results for the Magnetic Field density is shown in 8. In this scenario we show the magnetic field density in the spring for one of the parameterized studies. for this case the current is set at 2Amps while the displacement away from the equilibrium point is 0.25in. The force density and the Magnetic field intensity for the same scenario are also shown in Figs. 910.

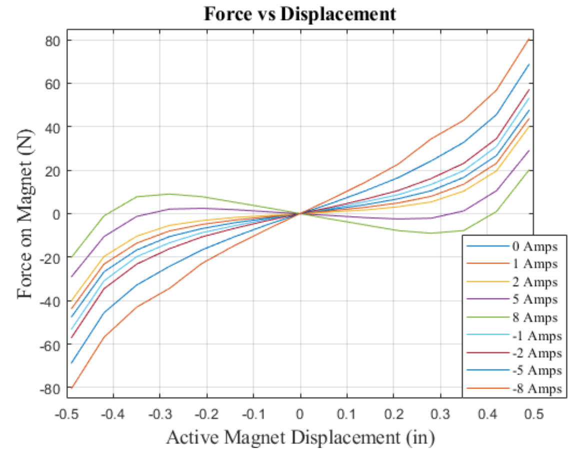


Fig. 6: Force on moving magnet

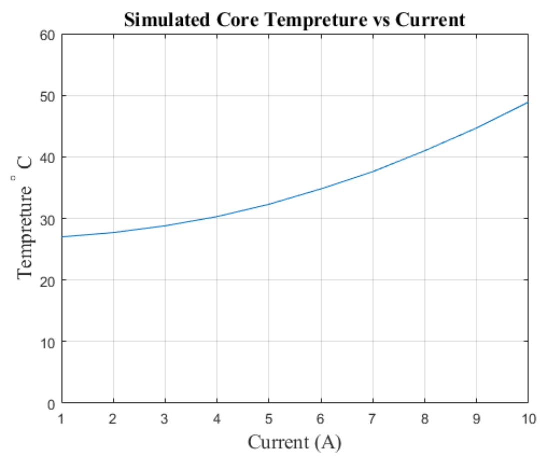
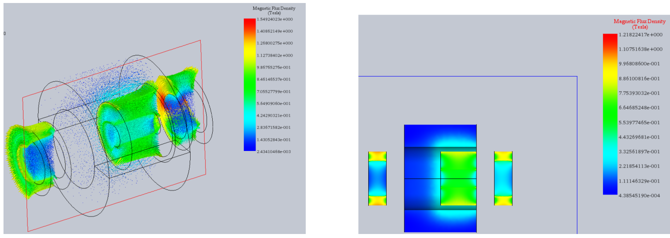


Fig. 7: Simulated Core temperature of spring

A. Problems Encountered

1) Cavities and Interference: While setting up the geometry of the spring for EMS simulation. It was noticed that even with Solidworks cavity feature, some geometries still cause interference. Such interference in the assembly usually gave incorrect simulation results. Such interference happened with annular features especially the magnets. The interference was mostly between the inner surface of the annular magnet and the large air-box surrounding the whole assembly. That was solved by adding air cylinders on the inside of the annular magnet and subtracting that as well from the surrounding Airbox.

2) Zero Contact Simulation: Even though the physical spring is able to reach a point of contact between the moving magnet and the stationary ones. That is why the magnet separation has been kept a little over the contact distance and on a range of [0.01 0.99]. These numbers with the provided meshing numbers gave accurate simulation results. These results were compared to magnet strength libraries for verification.



(a) (b)

Fig. 8: Magnetic Field Density

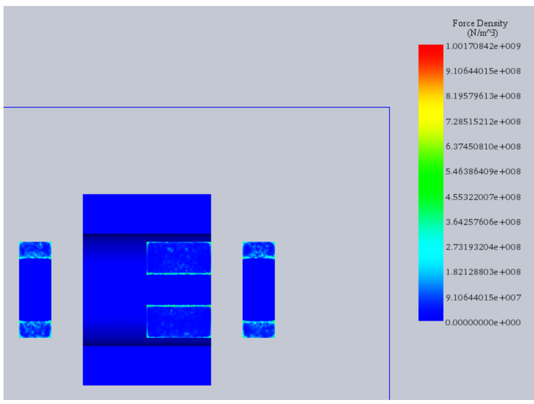


Fig. 9: Force Density

V. Conclusion

In this white paper we demonstrated the use of EMS software provided by EMWorks to simulate an electromagnetic spring for robotic gripper purposes. The simulated results shown in this paper support the viability of the design of the variable stiffness spring.

VI. future work

In the future we would like to verify the simulated results by building an actual prototype of the actuator. Moreover, we will perform more simulations that involve transient and dynamic responses to simulate the behaviour of the spring under variable loading conditions.

Acknowledgment

We would like to express our gratitude to the EMWorks for providing a license for EMS software for academic research purposes.

References

[1] G. A. Pratt and M. M. Williamson, "Series elastic actuators," in *Proceedings 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots*, vol. 1, 1995, pp. 399–406 vol.1.

[2] Y. Sun, P. Tang, J. Zheng, D. Dong, X. Chen, L. Bai, and W. Ge, "Optimal design of a nonlinear series elastic actuator for the prosthetic knee joint based on the conjugate cylindrical cam," *IEEE Access*, vol. 7, pp. 140 846–140 859, 2019.

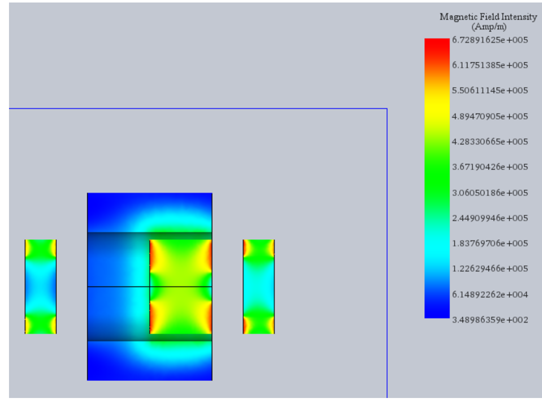


Fig. 10: Magnetic Field Intensity

[3] A. Schepelmann, K. Geberth, and H. Geyer, "Compact nonlinear springs with user defined torque-deflection profiles for series elastic actuators," in *Proceedings of (ICRA) International Conference on Robotics and Automation*. IEEE, May 2014, pp. 3411 – 3416.

[4] S. Wolf, G. Grioli, O. Eiberger, W. Friedl, M. Grebenstein, H. Höppner, E. Burdet, D. G. Caldwell, R. Carloni, M. G. Catalano, D. Lefeber, S. Stramigioli, N. Tsagarakis, M. Van Damme, R. Van Ham, B. Vanderborght, L. C. Visser, A. Bicchi, and A. Albu-Schäffer, "Variable stiffness actuators: Review on design and components," *IEEE/ASME Transactions on Mechatronics*, vol. 21, no. 5, pp. 2418–2430, 2016.

[5] R. V. Ham, T. G. Sugar, B. Vanderborght, K. W. Hollander, and D. Lefeber, "Compliant actuator designs," *IEEE Robotics Automation Magazine*, vol. 16, no. 3, pp. 81–94, 2009.

[6] "EMS," https://www.emworks.com//, 2022.