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Benefits and challenges of mechanical spring systems for energy storage applications

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Abstract

Storing the excess mechanical or electrical energy to use it at high demand time has great importance for applications at every scale because of irregularities of demand and supply. Energy storage in elastic deformations in the mechanical domain offers an alternative to the electrical, electrochemical, chemical, and thermal energy storage approaches studied in the recent years. The present paper aims at giving an overview of mechanical spring systems' potential for energy storage applications. Part of the appeal of elastic energy storage is its ability to discharge quickly, enabling high power densities. This available amount of stored energy may be delivered not only to mechanical loads, but also to systems that convert it to drive an electrical load. Mechanical spring systems' benefits and limits for storing macroscopic amounts of energy will be assessed and their integration with mechanical and electrical power devices will be discussed.

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Keywords:energy storage; mechanical springs; energy storage density.

1. Introduction

Sustainability of future energy systems from an environmental and economic point of view needs to overcome several challenges and technical aspects. Some challenges, such as the shift from fossil to renewable energy sources and the reduction of anthropogenic CO_2 emissions, are already being addressed [1-3]. However, intermittent energy provided by renewable sources has introduced new challenges in the energy sector.

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While the existing electricity grid results unchanged, solar and wind power have seen a large expansion during these years[4]. Therefore, the current electricity system is un-optimized and in need of adjustments. The electricity transmission grid needs to be adapted from the larger scale production sites used today to smaller local energy production sites. Energy storage solutions are being implemented to compensate for the fluctuations in intermittent energy production [5-6].

There is a wide range of different technologies to store electrical energy. A widely-used approach for classifying such systems is the determination according to the form of energy used. In particular, energy storage systems are classified into mechanical, electrochemical, chemical, electrical and thermal energy storage systems [7].

The most common mechanical storage systems are pumped hydroelectric power plants, compressed air energy storage (CAES) and flywheel energy storage [8]. Electrochemical storage systems consist of various types of batteries (lead acid, NiCd/NiMH, Li-ion, metal air, sodium sulphur, sodium nickel chloride and flow battery) [9]. Chemical energy storage focuses on hydrogen and synthetic natural gas (SNG) as secondary energy carriers [10-13] and, finally, electrical storage systems include double-layer capacitors and superconducting magnetic energy storage.

As far as mechanical energy storage is concerned, in addition to pumped hydroelectric power plants, compressed air energy storage and flywheels which are suitable for large-size and medium-size applications, the latest research has demonstrated that also mechanical springs have potential for energy storage application [14].

On the basis of results recently published, the present paper constitutes an overview on the application of solid elastic systems to mechanical energy storage and aims at assessing benefits and limits of this technology for what concerns energy density, power density, energy conversion and release.

2. State of the art and discussion

Elastic potential energy storage in components of mechanical systems occurs when they are deformed if forces are applied to the system. A well-known elastic component is a coiled spring. The elastic behavior of springs and elastic potential energy per unit volume can be found in literature [14-15].

Recent findings in the use of carbon nanotubes for storing energy and powering mechanical and electrical systems have shown that solid elastic systems have great potential in energy storage applications [14]. Nevertheless, springs are elastic parts that have been applied commonly in mechanical products for centuries.

Several studies recently published have rediscovered such elastic devices as storage technologies for power generation systems. In particular, flat spiral springs have been investigated in [15-17] and characterized for the above-cited application through the use of finite element stress analysis, modal analysis and dynamic analysis. A power generation system based on the coupling of a flat spiral spring with a double-fed motor was theoretically proposed in [15-17] but not developed and tested experimentally. Grid electrical energy drives the motor to coil tightly the spring through the transmission system, in order to store deformation energy. In the process of releasing energy, the control system drives the double-fed motor to work as a power generator and control the spring to release the deformation energy to put the double-fed motor in motion by the transmission system. By the means of modal analysis three different sections of the spring were investigated in order to provide a reference for spring's structure design [16].

Flat spiral springs were studied to be coupled with a planetary gear assembly in order to give a proof of concept of a low-cost kinetic energy recovery system (KERS) [17]. The energy that is lost during braking is stored in a spring by virtue of torsion force. Energy storing and releasing operations are done gradually and uniformly by the use of the combination of internal gears and spur gears.

A U.S. patent registered in 2010 [18] proposes a torsional spring, that is attached to a regenerating gear and a power shaft. Power shaft is, in turn, coupled with a power drive gear. As the torsional force is released it causes the power drive gear to rotate. The transferred energy, increased by the use of gearings, is then introduced to a conventional electric power generator. A scheme of the proposed technology is given in Figure 1 a).

Spring is controlled by a control circuit coupled also to the spring recharge unit, that generates the recharge control signal and the output control signal, based on the monitor signal.It is based on a status parameter of the spring system such as a torque or rotational velocity.In operation, the spring releases the stored energy in response to an output control signal generated by the control module in response to the monitor signal [18].

Other than conventional steel springs of various geometries, as said above, recent papers have demonstrated the potential of innovative springs based on carbon nanotubes (CNT) [14, 19-20].

CNT springs differ from conventional steel springs in mechanical properties, such as a high effective Young's modulus of about 1 TPa and experimentally demonstrated elastic strains as high as 6%, with theoretically predicted strains as high as 20% [1]. CNT yarn investigated in [14, 19, 20] is shown in Figure 1b).

In order to demonstrate the capability of CNT systems to drive mechanical and electrical loads, the authors tested CNT yarns in three different demonstration systems: CNT yarn slingshot, a CNT-driven piezoelectric cantilever and a CNT-driven electromagnetic generator.

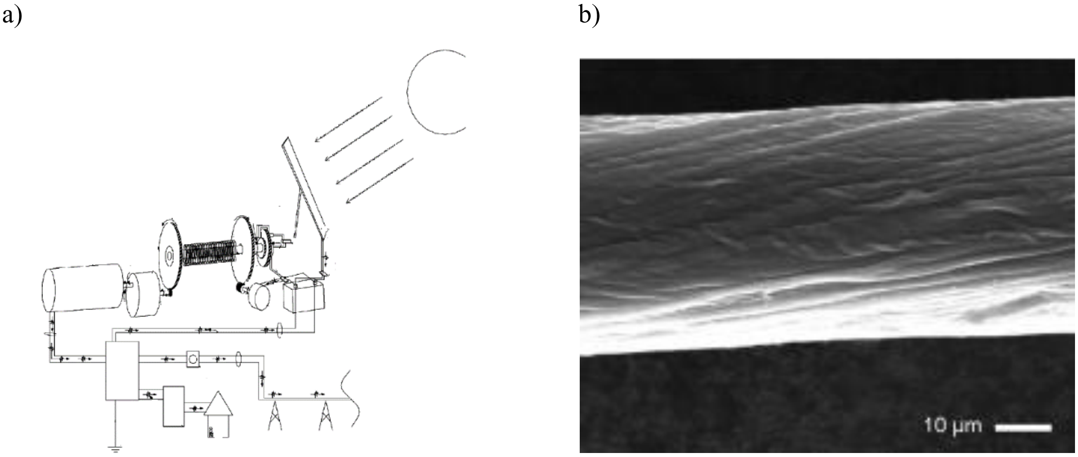

Fig. 1. (a) Energy storage technology based on conventional torsional spring [18]; (b) SEM image of CNT yarn used as energy storage device [14, 21].

In order to drive the piezoelectric cantilever, one end of the yarn is attached to a driving gear connected to a ratchet, and the other end is connected to an escapement mechanism via a series of transmission gears. The yarn in tension applies a torque to the escapement mechanism via transmission gears in order to regulate the rate at which energy is released. During operation, one of the transmission gears periodically collides with the piezoelectric, which converts the oscillation mechanical energy into electricity. The authors measured an output energy of $4.15 \cdot 10^{-8}$ J, corresponding to an average output power of 1.2 nW for a 35 s run time. The efficiency of the energy conversion is 0.01% [14].

Vibration energy harvesting, through the use of linear and nonlinear piezoelectric systems, has been studied in recent years and proved experimentally by [22-23]. Very low values of the overall efficiency need to be improved by reducing energy loss mechanisms and hysteresis losses.Indeed, hysteresis, and stress softening are all phenomena that have been observed [14].

Electromagnetic generators are also studied in couple with mechanical springs, since they operate well at high velocities, and therefore are well suited to convert the energy released rapidly from a spring.For a 100 ms run time with CNT yarn use, the output energy was 3.4 mJ with a maximum efficiency of 23% [14].

There are also papers in which multiple spiral steel springs are coupled with permanent magnet synchronous motor to store elastic energy. Dynamic modeling and control of the system are proposed in [24]. A patent [25] covers a self-sustaining electrical power generating system constituted by a permanent magnet linear electrical generator, a springs system associated with mechanical compression, release mechanism and supplementary linear DC electric motor.

A permanent magnet linear electrical generator converts the stored energy of the springs system into electric power. The generated electrical power feeds electrical loads via an electric convertor and a linear DC electric motor via an electric regulator. The linear DC electric motor converts the generating electrical power into magnetic field power that has a frequency equal to the natural frequency of the oscillated springs system after releasing. The magnetic field power applied to the springs enhances the oscillation movement of the springs and drives the permanent magnet armature of the linear electric power generator in linear velocity. Compression of springs can be carried out through jacks or hydraulic system.

Energy data about mechanical spring systems collected from literature papers are summarized in Table 1. For sake of comparison, data about other energy storage technologies are also added. A comparison of data in Table 1 indicates that the energy density of the yarns exceeds significantly the energy density of steel springs, opening new research paths in mechanical energy storage applications.

Table 1. Energy data on spring-based energy storage systems.

Reference	Power density	Gravimetric energy density	Volumetric energy density
Steel coiled spring [26]	-	0.14 kJ/kg	1080 kJ/m^3
CNT yarn spring [21]	-	4.20 kJ/kg	4900 kJ/m^3
CNT yarn spring-driven electromagnetic generator [14]	2500 W/kg	0.88kJ/kg	1770kJ/m^3
Twisted CNT [22]	-	8.30 kJ/kg	-
Batteries [5]	100-2000 W/kg	20-576 kJ/kg	54000-1.6·10^6 kJ/m^3
Compressed Air Energy Storage [5]	-	12.60 kJ/kg	18000 kJ/m^3
Flywheel Energy Storage [5]	12000 W/kg	18-360 kJ/kg	-
Supercapacitors [5]	800-20000 W/kg	7-100 kJ/kg	36000 kJ/m^3

Comparing CNT springs performances with those of other technologies, they lag behind the energy densities of rechargeable batteries.

The order of magnitude of CNT springs' energy densities is comparable with that of CAES, flywheels and supercapacitors. Even if at an early stage, CNT springs have a power density that is comparable to batteries.

3. Conclusion

Conventional mechanical springs coupled with electromechanical devices for energy storage and conversion are not investigated experimentally, but just studied theoretically. Some solutions are covered by patents. A new interesting research front is based on the use of carbon nanotube springs. CNT springs have been tested together with piezoelectric cantilevers and electromagnetic generators. On the basis of these experimental investigations, it was proven that CNT storage systems give energy densities that are higher than those of conventional steel springs, and indeed comparable to other mechanical energy storage technologies. In addition, these systems have high power density, comparable to that of batteries.

Hysteresis occurs and can reduce the output energy. Further evaluation ofthe effect of this phenomenon is needed, as well as more experimental data on the coupling of springs with electromechanical conversion systems and related overall efficiencies.

4. Copyright

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