Novel cryogenic motion control for aerospace

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In this paper two types of novel cryogenic mechanisms are exhibited, which has been designed using high-temperature superconducting (HTS) and magnetostrictive materials. Magnetostrictive materials have lead to a variety of large-stroke, high-force actuators at cryogenic temperature, which was previously difficult to make and is now much easier. Using HTS tapes in magnet takes advantage of the cryogenic temperature environment for added motive efficiency. Innovative actuator or motor designs using HTS magnet with the application of specific drive electronics bring out efficient, compact, and lightweight actuator systems for aerospace.

INTRODUCTION

A single advance in material science can lead to rapid progress in the related technologies of application. The invention of giant magnetostrictive material, called smart materials, is such an advance. A rare earth Giant Magnetostrictive Materials (GMM) including terbium(Tb) and dysprosium(Dy) demonstrate very high performance, magntostrain of 0.1-0.2%. Since having excellent magnetostriction over a broad range of temperatures from near absolute zero to above 400K, they also are ideal for cryogenic device application. These materials have lead to a variety of large-stroke, high-force actuators at cryogenic temperature, which was previously difficult to make and is now much easier. Some of these actuators meet the requirements of applications in special field such as aerospace. Actuators in the aerospace are used for restraint and release of deployable components of the mechanisms such as antennas, booms, and other appendages. Drive mechanisms supply the energy needed to move the components for precision position motion. Solenoids, voice coils and electric motors can be used to provide the desired motion [1,2].

Another advance in materials science that impacts the application of magnetostriction is a radical reduction in the size and an increase in the current-carrying capabilities of HTS magnets. For cryogenic temperature applications, such as deep aerospace, there is the search program for the origin of the universe. For searching red-shifted stars, which correlate to astronomical time, the more red-shifted a star’s spectrum is, the older the star is. In order to observe best the red-shifted stars in the infrared spectrum, the temperature of the telescope as Next Generation Space Telescope (NGST) should be as cold as possible, to keep the background interference as small as possible, because reduced thermal noise is highly desired for improving the instrument resolution. Mission concept studies for NGST suggest that the optical surface should be at 30K. This also requires the mechanisms in the telescope to operate at that temperature. For operation at higher than 10K and below 77K, the HTS offer an attractive opportunity to incorporate the HTS into mechanisms while taking advantage of their persistent mode of operation, i.e., the magnetostrictive material will maintain a train field without power[3].

These two factors work synergistically in generating mechanical movement and producing force at cryogenic temperatures. Consequently, the potential exists for the quick advancement of related techniques for producing cryogenic temperature actuators and mechanisms.

The object of this paper is to review the present situation from the point of view of the working principle of the mechanisms and their applications at cryogenic temperature. Novel constructs and motion control capabilities of two types of the rare earth magnetostrictive devices incorporated with HTS, an actuator and a linear stepping motor, were exhibited at the cryogenic condition.

MAGNETOSTRICTIVE LOW-TEMPERATURE ACTUATOR

The magnetostrictive materials have the coupling characteristic between their magnetic and mechanical states, which means a change in one of these states will produce a change in the other. A designed actuator, comprising a rod made of the rare earth TbDyFe magnetostrictive alloy and a HTS solenoid surrounding the TbDyFe rod for magnetic excitation, is shown in Figure 1. One end of the rod is anchored to the backup structure and the other end is extended out. The application of small triggering magnetic field, for instance, will cause the device to elongate and a high force, either push or pull, is activated. The superconductivity of the solenoid minimizes electric power dissipation contributing to energy efficiency and to reduction of waste heat, which must be removed to maintain a cryogenic environment.

The drive electronics consists of a precision current regulator, an overcurrent protection circuit and an efficient DC/DC converter. The combination control of the drive accurately maintains the current through the actuator to hold a position.

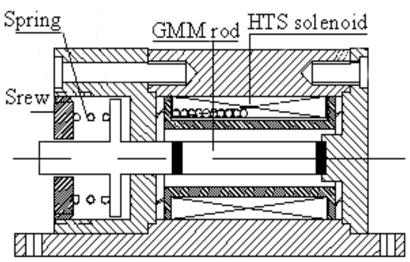


Figure1 an actuator

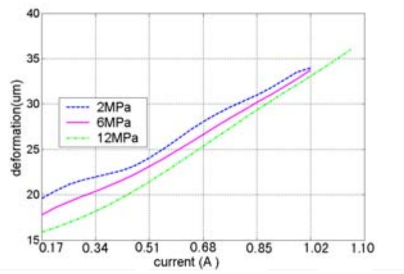
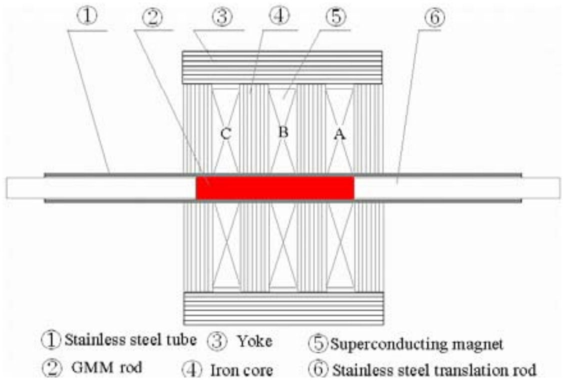


Figure 2 current- deformation curve under different pressure

This lightweight actuator could be utilized for performing shape and position control functions for the telescope to operate at cryogenic temperature in the deep space. Precision positioning can be achieved by precisely controlling the current energizing the HTS solenoid of the actuator. Such a simple actuator can also be used for precise mechanical positioning, vibration control, or switch and valve operation having strokes up to more than 35 μm (see Figure 2) and force capabilities up to 1200N.

LINEAR STEPPING MOTOR

A magnetostrictive linear translation mechanism has been designed to function as a micropositioning device at cryogenic temperatures, in which there are requirements for high stiffness, increments of motion $<1\,\mu m$, and long travel of several millimeters. A stepping motor is developed by a traveling active element which is a rare earth magnetostrictive rod in a tight-fitting tube which is exited by the traveling magnetic field from superconducting pancake coils (see Figure 3). These pancake coils are supplied by polyphase current to bring the stepping motion. The stepping motor includes high force motion and the ability to hold position when powered off. These capabilities are completed with a single set of electronics (see Figure 4).



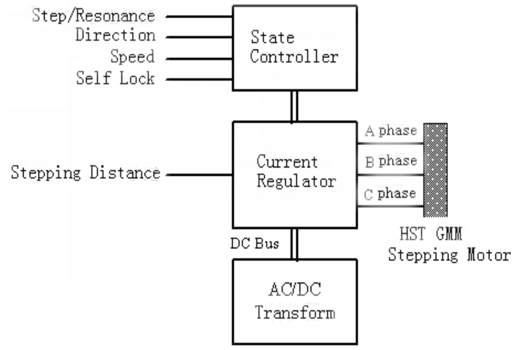


Figure 3 linear stepping motor

Figure 4 electronics of the stepping motor

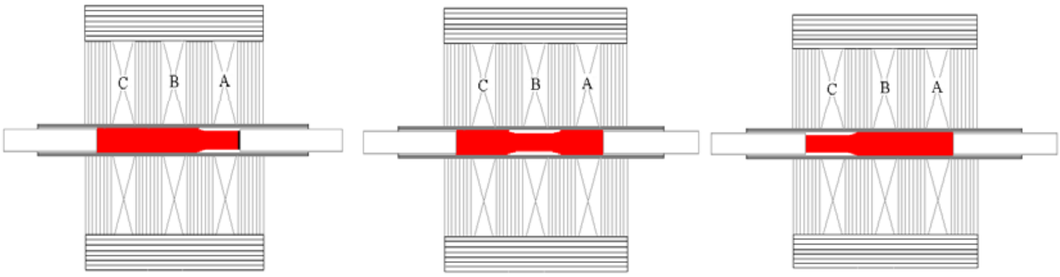
The peristaltic principle of the linear stepping motor (see Figure 5) is described as below. The powered off condition is depicted in Figure 3, where a length of magnetostrictive element with circular section is confined to the tube. When no magnetic field is applied to the element, there exists a tight fit between the tube and the element. This squeeze preloading produces the normal force necessary for fail-safe joint locking.

When the coils of the phase A are powered , the magnetic field begins to interact with the magnetostrictive element under the phase A ranges. Because the magnetostrictive element under the phase B and C range is embedded, the magnetostrictive element under the phase A range is expanded along the magnetic field, extending to the right to push the right staff (see Figure 5 (a)).

In the second step, the phase A is powered off and the phase B are powered, the magnetostrictive element under the phase A and C range is embedded and the magnetic field begins to interact with the magnetostrictive element under the phase B range. Consequently the magnetostrictive element under the phase B range is expanded along the magnetic field too(see Figure 5 (b)), while keeping the same length as Figure5(a).

In the third step, the magnetostrictive element under the phase C range is expanded along the magnetic field (see Figure 5 (c)), keeping the same length as Figure5(a).

In the next step, phase A again is powered, extending to the right to push the right staff, while phase C is powered off, pulling the left staff from the left to the right. The magnetostrictive element has effectively moved to a right step. If the coils of the stepping motor are powered in the pattern sequence as -A-B-C-A-…, the magnetostrictive element will effectively move to the right to push the loads step by step.



(a) (b) (c)

Figure 5 peristaltic principle of the stepping motor

The performances of the high temperature superconducting and giant magnetostrictive linear stepping motor are：

1.superconducting magnet with the iron core
2.large stroke
3.large force
4.adjustive micro-step
5.self lock function when powered off

Such micropositioners could be used to make fine position adjustment in diverse scientific and industrial instruments. For example, they could be used to drive translation stages in scanning tunneling microscopes or to move optical elements that must be located at long but precise distances from each other, including telescopes and interferometers for cryogenic deep space application.

OTHER APPLICATIONS

Other applications of these magnetic actuators take advantage of their high force capability, large stroke and desirable repeatability.

1. Resonant frequency control of RF cavities for particle accelerators

High temperature superconducting particle accelerators use a bellows shaped resonant cavity to impart energy to the particle with radio frequency waves. To achieve the particle energies for experiments, hundreds of cavities must work in tandem at the exact same frequency. Frequency matching is accomplished by squeezing the cavities axially. The high force capability combined with the sub-micron positioning capability of the actuators is well suited to this application at the cryogenic environment.

2. Active vibration control

These actuators can be applied to active control of vibration. With state-of-the art accelerometers and control electronics, active vibration control systems are being developed for both cryogenic and room temperature application. Magnetic vibration control is more efficient than the currently available piezoelectric systems for controlling low frequency high amplitude vibrations.

CONCLUSION

Novel mechanisms designed using HTS magnet and magnetostrictive materials,with the application of the specific drive electronics, results in efficient, compact, and lightweight actuator or motor systems. The potential exists for the quick advancement of related techniques for producing actuators and mechanisms at the cryogenic temperature environment.

ACKNOWLEDGMENT

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