NASA/TM-2000-209139

A Cryogenic Magnetostrictive Actuator Using a Persistent High Temperature Superconducting Magnet

Part 1: Concept and Design

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June 2000

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ABSTRACT

Cryogenic magnetostrictive materials, such as rare earth zinc crystals, offer high strains and high forces with minimally applied magnetic fields, making the material ideally suited for deformable optics applications. For cryogenic temperature applications, such as Next Generation Space Telescope (NGST), the use of superconducting magnets offer the possibility of a persistent mode of operation, i.e., the magnetostrictive material will maintain a strain field without power. High temperature superconductors (HTS) are attractive options if the temperature of operation is higher than 10 degrees Kelvin (K) and below 77 K. However, HTS wires have constraints that limit the minimum radius of winding, and even if good wires can be produced, the technology for joining superconducting wires does not exist. In this paper, the design and capabilities of a rare earth zinc magnetostrictive actuator using bulk HTS is described. Bulk superconductors can be fabricated in the sizes required with excellent superconducting properties. Equivalent permanent magnets, made with this inexpensive material, are persistent, do not require a persistent switch as in HTS wires, and can be made very small. These devices are charged using a technique which is similar to the one used for charging permanent magnets, e.g., by driving them into saturation. A small normal conducting coil can be used for charging or discharging. Very fast charging and discharging of HTS tubes, as short as 100 microseconds, has been demonstrated. Because of the magnetic field capability of the superconductor material, a very small amount of superconducting magnet material is needed to actuate the rare earth zinc. In this paper, several designs of actuators using YBCO and BSCCO 2212 superconducting materials are presented. Designs that include magnetic shielding to prevent interaction between adjacent actuators will also be described. Preliminary experimental results and comparison with theory for BSSCO 2212 with a magnetostrictive element will be discussed.

Keywords: actuator, cryogenic, magnetostriction, NGST, optics, persistent, superconductor, Terzinol

INTRODUCTION

One goal of the NASA Origins program is the search for the origin of the universe. The Origins program is a NASA Headquarters Space Science Program that includes several telescopes that will explore deep space. These telescope missions, such as the Next Generation Space Telescope (NGST), will be searching for red-shifted stars which correlate to astronomical time, the more red-shifted a star's spectrum is, the older the star. Red-shifted stars are best observed in the infrared spectrum. To keep the background interference as small as possible, the temperature of the telescope should be as cold as possible. Mission concept studies for NGST suggest that the optical surfaces should be at 30 K. This also requires the actuators to operate at that temperature. During the NGST mission, the telescope will be in the observatory mode most of the time during which the optics must remain stable and within performance specifications. The actuators that adjust the optical figure of the primary mirror must remain motionless without power during the observatory mode of NGST. This capability is what has been referred to as "set and hold with power off."

For operation at 30 K, the high temperature superconductors (HTS), such as YBCO and BSCCO 2212, offer an opportunity to incorporate these materials into actuator concepts while taking advantage of their persistence. These HTS materials are available in two forms, wire and solids. For applications using HTS wires, a persistent switch which has two states, one that shorts at cryogenic temperature and opens at high temperature must be used. At the present time there is no reliable technique for joining two HTS wire as would be required in a persistent switch. HTS solids are less expensive and do not require persistent switches like the HTS wire. An actuator concept will be described in this paper that could be used on NGST class telescope missions and which uses HTS solids or monoliths.

ACTUATOR CONCEPT

The persistence capability of HTS materials is very attractive for potential application to actuator concepts that must have set and hold with power off capability and that must operate at cryogenic temperatures. A material that has high strain capability at cryogenic temperatures is the "giant magnetostrictive" material Terzinol. This material is a single crystal grown from Terbium, Dysprosium, and Zinc (TbDyZn). Single crystals of this material have strains as high as 0.5%. For example, a TbDyZn crystal 25.4mm (one-inch) in length could change length by 127μm (.005 inches or 5 mils). This length change is more than is usually required for fine tuning optics during on-orbit operations for changes due to thermal gradients. Schematically, this type of actuator would be part of a two-tiered actuator system between the primary mirror backup structure and the primary mirror as shown in Figure 1.

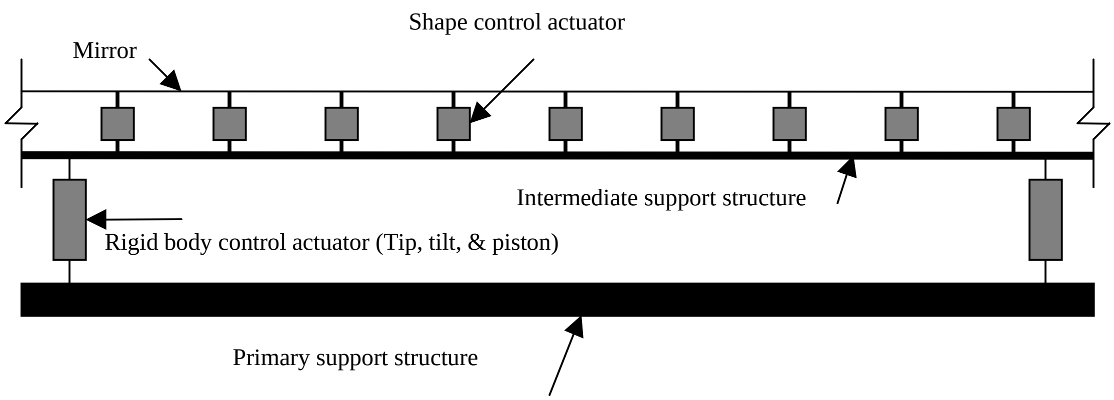

Figure 1: Two-tier actuator arrangement

The TbDyZn crystal is a magnetostrictive material that requires a magnetic field to align the magnetic domains. As higher and higher magnetic fields are applied to the TbDyZn rod, the magnetic domains within the rod are rotated more and more. This domain rotation causes the rod to change length until the applied field saturates the TbDyZn rod and the maximum length change is achieved. A sketch of this actuator is shown in Figure 2.

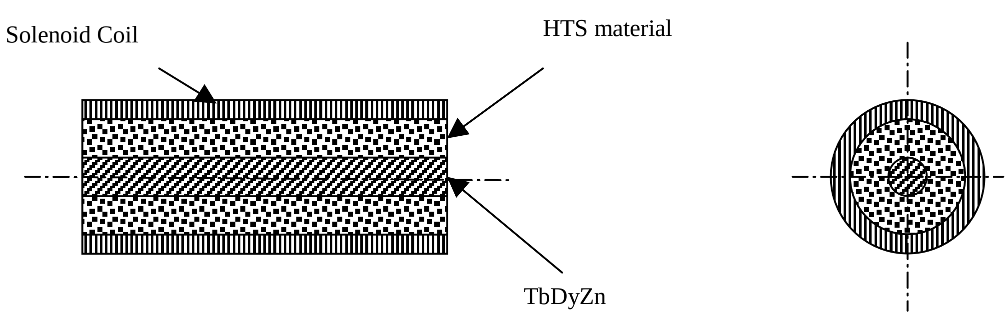

Figure 2: Schematic of actuator

Normally, a solenoid coil is placed around the magnetostrictive rod to provide the magnetic field needed to cause the rod to change length. If a solenoid coil were used, continuous power would need to be supplied to the coil to keep the magnetostrictive rod strained. This has several drawbacks. First, the heat dissipation from the coil would be detrimental to keeping the primary mirror of the telescope cold. Secondly, power would need to be supplied continuously which violates the actuator requirement that it should hold position (strain) with power off. To overcome these drawbacks, we turn to the HTS monoliths.

An actuator is proposed consisting of a charging circuit, a superconducting monolith tube, a Terzinol actuation rod, and a magnetic flux confining case. These components are described below.

CHARGING MECHANISM

Induction charging of superconducting monoliths (bulk material) has been attempted with low temperature superconductors. In the 1970s the technique of flux trapping was used by a Stanford University group led by Rabinovich to study the persistent magnetic field trapped in low-T_c superconductors. Recently, flux trapping has been studied using YBCO at high and low temperatures and for BSCCO at high temperature. The University of Texas[1,2,3] obtained the most impressive performance of flux trapping with YBCO at 77 K. High fields, as high as 10 T at 50 K, can be produced with a YBCO single crystal disk about 25 mm in diameter and 10 mm thick.

The charging mechanism used in the past consists of applying a magnetic field when the material is not superconducting, then decreasing the temperature until the material is superconducting, and finally removing the field[1,2,3]. This manner of charging is not convenient, as the sample needs to be cooled quickly, resulting in large thermal stresses. Cracks can develop during the cooling period. In addition, it is necessary to increase the temperature of the superconductor in order to alter the magnetic field. Finally, since the cooling is relatively slow, the external magnet field needs to be applied for long times (many seconds), complicating the design of the charging coils.

For the proposed actuators, a different manner of charging will be used. The basic principle consists in bringing the superconductor to its critical state, which occurs when the maximum superconducting current is achieved, and then applying additional fields at near-constant temperature. At the critical state, the magnetic flux can freely move in-and-out of the superconductor (flux pumping), with some dissipation, resulting in small increases in temperature due to the large thermal capacity at the temperatures of interest, 20-40 K. The HTS material at these temperatures does not experience quenching, and little evidence of flux jumping has been observed.

The superconductor can be driven to a critical state with the charging coil itself (flux pumping), or by a second set of coils that induce large enough currents in the superconductor that the critical state is reached at lower fields (saturation pumping). For the present actuators, the superconducting magnet and the charging magnet are solenoids. For the case of saturation pumping, the saturation coil is made from a toroidal winding around the superconductor. An attractive feature of this charging mechanism is that fast pulsed coils can be used, simplifying the design of the charging coils.

It is important to match the superconductor to the application, because of the need to drive the material to its critical state. YBCO material has very high critical current density and fields at the temperatures of interest (20-40 K), and is difficult to machine. The self-fields for YBCO are on the order of 10 T for 10-20mm diameter disks. BSSCO-2212 material on the other hand, is relatively easy to machine and has critical self-fields anywhere between 0.2-0.8 T for the same size. Lower fields can be obtained by machining the sample to smaller dimensions.

Figure 3 shows the critical self-fields of tests for BSSCO-2212 tubes as a function of temperature. The superconducting sample was a tube, 25mm OD and 40mm long, with 5mm walls. The field was measured on-axis at the sample mid-plane. The material was prepared by the centrifugal casting method[4]. The material and the thickness are appropriate for applications at 20-40 K with critical self-fields on the order of 0.2-0.6 T.

CHARGING CIRCUIT

Figure 4 shows a simple schematic of the electrical circuit. A power supply is used to charge a capacitor, which is discharged through the charging coil L1. The superconductor is represented as an inductor L2 in series with a variable resistor. The variable resistor models the superconductor, limiting the current to values lower or equal to the critical current. The variable resistor has zero resistance when the superconductor current is below critical.

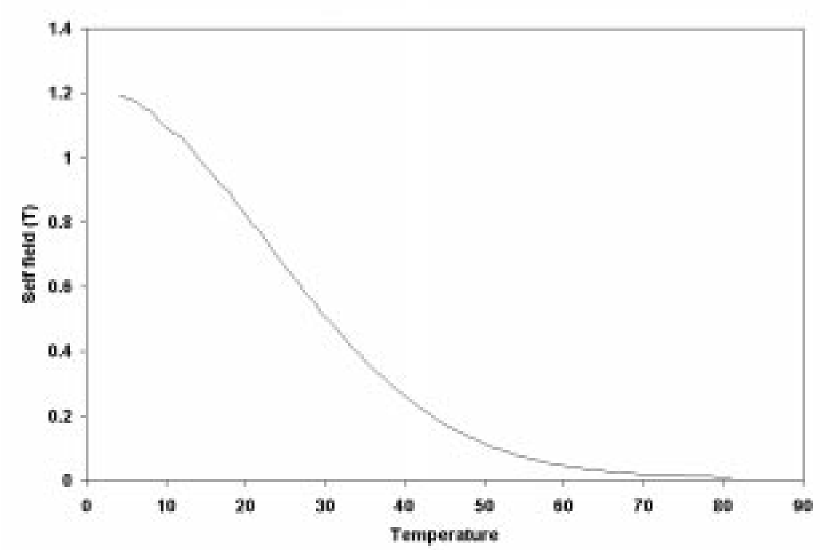

Figure 3: Critical self-field vs. temperature (K) of a 25 mm OD BSCCO 2212 sample

It is assumed that the charging coil and the high-T_c tube have good coupling coefficient. The currents in the charging coil and the induced current in the high-T_c tubes are shown in Figure 5. As the switch, S2, is closed, since the coils are well coupled, the circuit looks like a short circuit, and the current rises rapidly. Increases in current in the charging coil, L1, are balanced by opposite changes in current in the superconductor, L2. As the high-T_c superconductor reaches critical conditions, the current in the superconductor remains steady at critical, and the load suddenly looks inductive, slowing down the rate of rise of the current. The circuit looks like a coupled capacitor-inductor system, with a LC time constant. After the charging circuit current reaches the maximum current and the current starts decaying, the superconductor is moved away from the critical condition, and suddenly the inductive load disappears and the circuit becomes a short circuit, with no voltage but large current. With no driving voltage, the current in the charging coil decreases very fast, without oscillations. The final result is that the energy in the capacitor, minus the energy dissipated in the charging coil, is transferred to the superconductor.

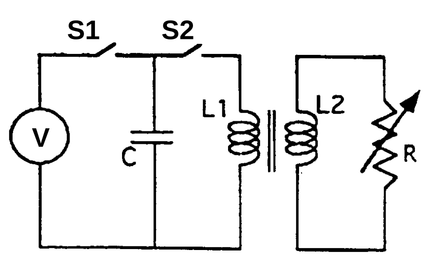

Figure 4: Schematic diagram of power supply

The process can be repeated until the right current in the superconductor is reached, as long as it is below the critical current. The discharging process is the opposite, with the capacitor charged in the reverse direction.

The switch can be a semiconductor switch, realized with either a fast-insulated gate bi-polar transistor (IGBT) or a high power MOSFET. It is also necessary to match the impedance of the load by using a transformer between the power supply and the charging coil.

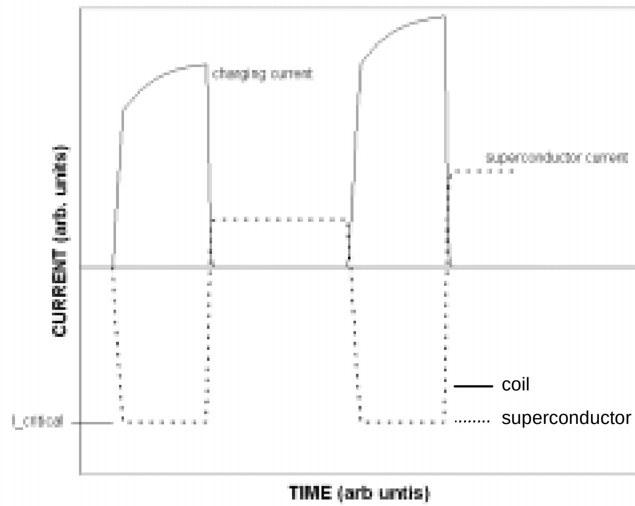

Figure 5: Current waveforms in charging and superconducting coils

LOW TEMPERATURE MAGNETOSTRICTIVE MATERIALS

The magnetostrictive material chosen for this project was a single crystal consisting of Terbium, Dysprosium, and Zinc in the stoichiometric ratio of $Tb_{.6}Dy_{.4}Zn_1$. The performance curves for this composition, now named Terzinol, are shown in Figure 6. The major advantage shown in Figure 6 is that only 500 Oersteds of applied field is necessary to achieve a large magnetostriction when operating at low compression. The choice of the composition used in this actuator was predicated by the early polycrystalline work in this system[5] that indicated that the $Tb_{.6}Dy_{.4}$ ratio would be a candidate material for further study. A single crystal was prepared and shown to possess a magnetostriction of 5000 parts per million[6]. This is a factor of three better than the available room temperature magnetostrictive material known as Terfenol-D. Another advantage is that this material can be formed to any shape using machine tools and can withstand greater shear loads. These factors lead to an increase in the design flexibility for magnetostrictive devices.

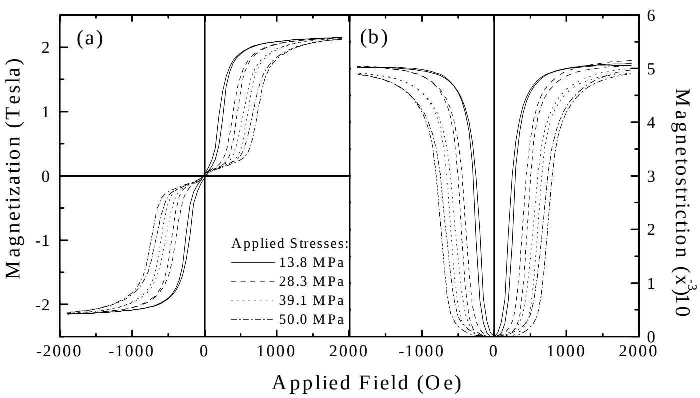

Figure 6: (a) Magnetization and (b) magnetostriction vs. field for $Tb_{0.6}Dy_{0.4}Zn$ at various axially applied compressive stresses at 77 K.

ACTUATOR DESIGN

Figure 7 shows a cross sectional view of the prototype actuator. The design principles are based on maintaining a magnetic circuit with a high flux density and a minimal pre-stress to allow the Terzinol to operate in an optimal state. References[5,6,7] provide design criteria information for magnetostrictive materials. The force transfer rod performs the function of a positioner for small loads.

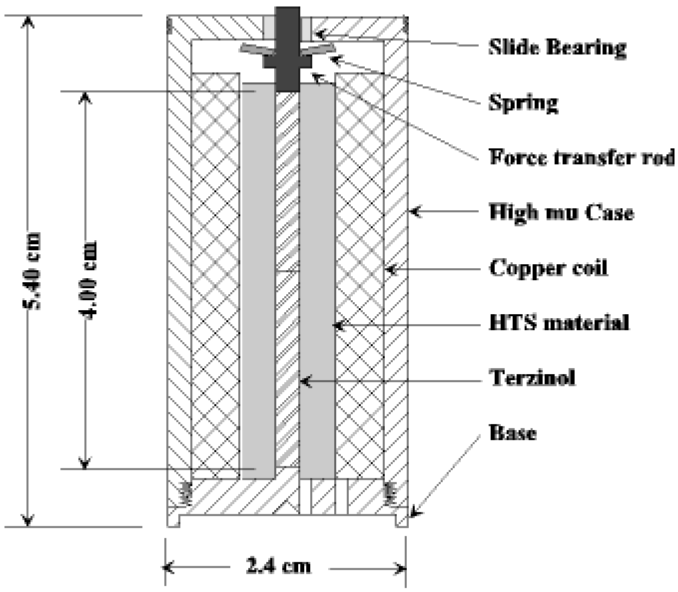

Figure 7. Diagram of actuator assembly showing a cross-sectional view.

CONCLUSIONS

A concept for a cryogenic actuator, using a TbDyZn magnetostrictive rod (Terzinol) with a magnetic field induced via a persistent HTS material, is presented. The actuator concept is simple, has no moving parts, and can be made small and compact. Research on this actuator is continuing and a prototype will be fabricated and tested in a cryogenic chamber. A demonstration is planned to show the actuator controllability and resolution of 20nm.

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 2000	Technical Memorandum

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
A Cryogenic Magnetostrictive Actuator Using a Persistent High Temperature Superconducting Magnet *Part 1: Concept and Design*	522-32-41-02
6. AUTHOR(S) Garnett Horner, Leslie Bromberg, and J. P. Teter	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199	8. PERFORMING ORGANIZATION REPORT NUMBER L-17837
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA/TM-2000-209139
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category 39 Distribution: Nonstandard Availability: NASA CASI (301) 621-0390	12b. DISTRIBUTION CODE

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14. SUBJECT TERMS	15. NUMBER OF PAGES
actuator, cryogenic, magnetostriction, NGST, optics, persistent, superconductor, Terzinol	12
	16. PRICE CODE A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL