Large Scale Magnetostrictive Valve Actuator

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Abstract

Marshall Space Flight Center's Valves, Actuators and Ducts Design and Development Branch developed a large scale magnetostrictive valve actuator. The potential advantages of this technology are faster, more efficient valve actuators that consume less power and provide precise position control and deliver higher flow rates than conventional solenoid valves. Magnetostrictive materials change dimensions when a magnetic field is applied; this property is referred to as magnetostriction. Magnetostriction is caused by the alignment of the magnetic domains in the material's crystalline structure and the applied magnetic field lines. Typically, the material changes shape by elongating in the axial direction and constricting in the radial direction, resulting in no net change in volume. All hardware and testing is complete. This paper will discuss: the potential applications of the technology; overview of the as built actuator design; discuss problems that were uncovered during the development testing; review test data and evaluate weaknesses of the design; and discuss areas for improvement for future work. This actuator holds promises of a low power, high load, proportionally controlled actuator for valves requiring 440 to 1500 newtons load.

Introduction

Magnetostrictive materials change dimensions when a magnetic field is applied; this property is referred to as magnetostriction. Magnetostriction is caused by the alignment of the magnetic domains in the material's crystalline structure and the applied magnetic field lines. Typically, the material changes shape by elongating in the axial direction and constricting in the radial direction, resulting in no net change in volume.

The response is proportional to the applied field strength and occurs in microseconds. Most metals exhibit this property. Nickel, for example, increases in length (strain) by approximately 40 parts per million in a sufficiently strong magnetic field. Materials which produce strains greater than 600 PPM are known as "giant" magnetostrictive or "smart" materials. Terfenol-D, produced by Etrema Products, Inc., produces strains from 800 to 1200 PPM in fields as low as 2000 Oersteds (Oe) and is, currently, the only commercially available magnetostrictive material. Even though this is considered to be "Giant" scale magnetostriction, the net motion is only 0.025 mm per 25 mm of material

The load carrying ability of the material is limited by the maximum stress the material can withstand; therefore, the load density is far greater than conventional actuators power systems. Current solenoids are limited to about 2.3 MPa, pneumatic systems to about 10 MPa and hydraulic system to 20 MPa. The yield strength of magnetostrictive materials is over 69 MPa, giving it a load density that is 3 times the best available. The material is only limited by the small stroke.

Discussion

Approach: The approach was to build a mechanical advantage system that will utilize a magnetostrictive actuator to operate a large valve (25-mm size) at high flow demand. ER33 hoped to demonstrate the valve will be as fast as a solenoid valve, precise as a hydraulic valve and lighter than either for its size.

Accomplishments: All hardware and testing is complete. The valve performance was acceptable, but strokes were not as predicted.

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Following the proposed plan, hardware for the magnetostrictive valve design (designed using ER funds prior to this effort), shown in Figure 1, was built within the first year of the effort. However, the valve could not be reasonably modified as an actuator, so a new design was developed. The newly designed actuator, shown in Figure 2, used lessons learned and some concepts from the original valve design.

Figure 1. Original Valve Design

Figure 1. New Valve /Actuator Design

Early testing revealed that Terfenol –D does not hold up well to high frequency responses. The material is very brittle and susceptible to cracking and fracture if improperly side loaded. Results of testing are shown in Figure 3. Also, the small motions in the actuator require machining to close tolerances, precise shimming to achieve correct preloads to obtain proper strain (elongation), and large magnetic biasing to maintain the proper pre-load on the material to prevent hysteresis. Figure 4 shows that the Terfenol D material hysteresis decreases and strain increases with preload. The design allowed for these adjustments in the preload using shims under the pre-load springs.

The material was loaned to a local contractor to perform tests to verify the response of the material to preload. The contractor presented data, shown in Figure 5 that differed from the theoretical data supplied by the material vendor, shown in Figure 4. This data was incorporated into the new design. The contractor derived curve, Figure 5, shows the hysteresis in the material measured as a load is applied to the end of a bar of Terfenol D. This is a plot of magnetic field line angles from the normal (axial) direction. The angle is directly related to the inverse relationship of magnetic input for a force output.

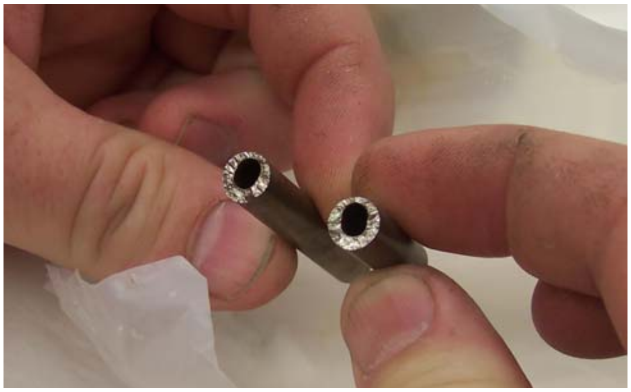

Figure 2. Terfenol-D Is Very Brittle.

After incorporating preliminary test results into the design, the fabricated hardware was assembled, as shown in Figure 6, and tested. During testing, several issues were discovered. The stroke of the valve was measured as 0.14 mm on the arm (multiplied) versus the expected stroke of 0.38 mm. Figure 7 shows the displacement measurement recorded during test. Investigation revealed that the magnetic field suggested by the vendor for magnetic biasing of the material was too high and caused the crystalline structure to begin to exhibit strain (elongation) before the electric field was applied. The magnets were eliminated and the valve coil repositioned resulting in a stroke of 0.22 mm, just over half the predicted stroke. Perhaps, using weaker magnets for the biasing would increase the stroke of the material, but time did not allow for this to be done.

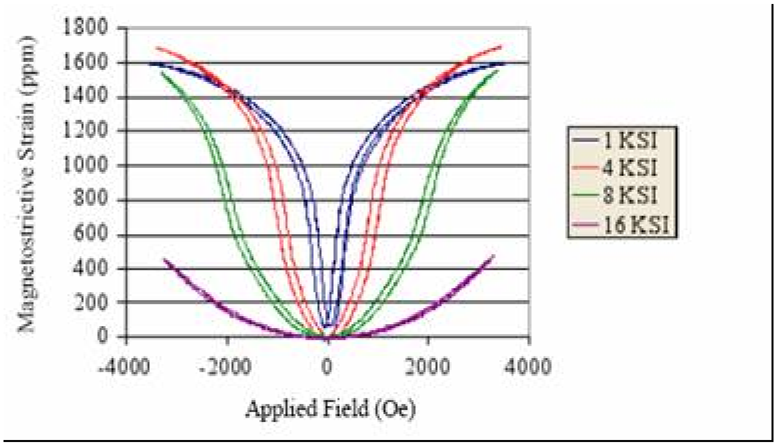

Figure 4. Material Hysteresis vs. Preload

Figure 5. Measured Hysteresis

Figure 6. Final Valve Assembly

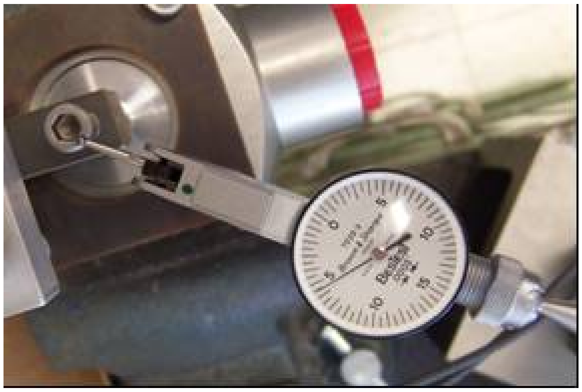

Figure 7. Original Displacement

Per design, the length of the coil was approximately half the length of the magnetostrictive material. The concept was to use the end effects of the shorter coil to provide strain to the material out side the coil, so the coil was centered on the material. This concept was not ideal and a new coil was ordered, but time did not allow testing with the new coil. During a review of the magnetic flux path design with a local vendor, it was suggested that the design may not accommodate an ideal path and the valve was "leaking" magnetic field strength. A possible solution to this issue is to replace the aluminum-bronze shield surrounding the coils with a new shield made of a magnetic material. These three changes, weaker magnets, a longer coil and a different shield material, could be easily incorporated into the design if time and budget allowed.

Planned Future Work: No current program has expressed interest in the technology. CLV is working to a low risk, existing technology approach. Future programs, such as LSAM, have inquired, but no technical risks have been identified where this technology would be useful. A Space Act Agreement with Orion will continue and ER33 plans to apply for some Innovative Partnerships Program funds to expand this development.

Publications and Patent Applications: ER33 has submitted a patent application for the magnetostrictive valve. The local company that performed the load testing on the materials has entered into a Space Act Agreement with MSFC to develop this into a marketable regulator for space craft application. Being proportional, fast, and small, this valve has the potential to be an electrical regulator and could provide a regulator system that has little or no change in regulation regardless of the required flow demand. This would improve pressure feed reaction control system performance, better control purges, allow active pressure control in propellant tanks, and a number of other advantages.

Conclusions

The data obtained during this effort has proven that the concept actuator design has merit, shown the valve design must be carefully controlled, and that the preload, coil design and flux path issues are critical to obtain the required stroke and repeatability. The valve met all design requirements except stroke. This problem has been evaluated and solutions developed, but not proven. The design could be modified to incorporate these improvements and regain the lost stroke.

Therefore, the concept has been shown to work, the multiplying lever system worked perfectly and the valve concept shows potential.

Additionally, newer materials are available that have larger strokes (Terfenol-D has 1200 PPM, newer materials have 5000 PPM potential). The design provided has proven that the use of magnetostrictive materials in valves is a viable concept. More time and better magnetic flux path design is needed to fully utilize the capabilities of this material.