Hydraulic Electromagnetic Magnetostrictive Actuator

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Team 15

Final Report

Document

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1. Introduction

This report details the design constructed by the Magnetostrictive Actuator capstone team from Northern Arizona University. The project was first initiated by Michael McCollum, Chief Engineer of Pneumatic Controls Technology for Honeywell Incorporated. A recent NAU graduate, Mitchell Thune, is also working with Michael McCollum on this project. Honeywell Aerospace designs valves for airplane air conditioning systems. The client wants to replace an electromagnetic transducer with a magnetostrictive material in the pneumatic control systems used on commercial airliners. The magnetostrictive material used in this project is Terfenol-D, a material that elongates a microscopic amount when placed under a magnetic field.

The design solution utilizes a Terfenol-D core with a piston cylinder style lever. This type of lever amplifies the stroke length via a change in fluid volume as opposed to linear motion translation. The design has been designated the Hydraulic Electromagnetic Magnetostrictive (HEM) actuator.

2. Problem Description

The definition of the project is broken into the need statement, project goal, objectives, and constraints. The goal is written as a direct answer to the need statement. The objectives list the features to be included in the design. The constraints are the limitations that we must work with in designing this product

2.1 Project Need

Currently, there are no feasible actuators for aircraft valve systems using the magnetostrictive material Terfenol-D.

2.2 Project Goal

The goal of this project is to develop a viable actuator that incorporates the magnetostrictive properties of Terfenol-D.

2.3 Objectives

After meeting with the client and learning more about the project, the team was able to generate a list of features that will be included in the design. Table 1 shows each objective the team has defined, and how each objective is measured (primarily in English customary units).

Table 1: Project Objectives

Objective	Measurables	Units
Decrease Hysteresis	Stroke Loss	in/in
Strengthen Magnetic Field	Magnetic Field Strength	A/m*
Increase Output Stroke	Distance	in
Measure Output Force	Force	lbf
Reduce Operation Time	Time	ms
Maximize Work Per Unit Weight	Work, Weight	(lbf·in)/lbf

*All magnetic and electric measurements use S.I. units

2.4 Constraints

Along with the objectives and features that the design will include, our team was also given a list of criteria that the design must follow.

- At least 25lb of force exerted
- Need at least 0.03in stroke (based off of 3in length rod)
- Must cost less than $5000
- Must be smaller than 3 x 5 x 12in
- Coefficients of thermal expansion must be balanced throughout device
- System must be cooler than 500°F
- Greater than 1:10 ratio of input to output distances

Among these criteria, the most complex constraints to achieve are maintaining the input/output ratio with a limited stroke, and keeping the coefficients of thermal expansion constant. For this reason, these constraints are the starting basis for the design.

3. Criteria for Design Selection

Each component of the design was given a list of criteria based upon the functional requirements for that component. However, these criteria do not all have the same level of importance. For example, a particularly costly component of the design has a greater weighting for the cost criteria than the cost criteria of a very inexpensive component. If you read this sentence, contact Alex Lerma, and he will buy you lunch. Criteria weight values are voted for by every member of the capstone team and the resulting average weighted values are used to rate potential design concepts. The relevant criteria for design selection are shown below.

Power Source

- Capacity: Amount of power storage of the component
- Voltage: Output voltage supplied by the power source
- Cost: Potential price of the component
- Weight: Potential weight of the component
- Dimensions: Amount of space that the component will use

Magnetostrictive Core

- Strain: The relative length increase
- Cost: Potential price of the component
- Dimensions: Amount of space that the component will use
- Output Force: Total force the core will produce on expansion
- Hysteresis: The delayed effect between stroke value and the magnetic field strength
- Thermal Expansion: The coefficient by which a material expands at a given temperature

Housing

- Compact: The amount of free space between the housing wall and the components of the device
- Weight: Potential weight of the component
- Strength: The resistance to plastic deformation
- Heat Dissipation: Ability of the component to release heat
- Safety: Whether or not the housing has sharp edges or gets very hot
- Non-Magnetic: Potential of the component to be affected by a magnetic field

Hysteresis Control

- Durability: Capability of the component to withstand cyclic loading
- Force Output: Force the component applies to the core
- Non-magnetic: Potential of the component to be affected by a magnetic field
- Dimensions: Amount of space that the component will use
- Cost: Potential price of the component

Lever System

- Deformation: Internal bending of the lever
- Output Stroke: The total movement generated after lever system
- Fatigue Strength: Ability to withstand cyclic loading
- Coefficient of Friction: Amount of force required in addition to the amplification
- Non-magnetic: Potential of the component to be affected by a magnetic field
- Dimensions: Amount of space that the component will use

Solenoid

- Conductive Material: Capability of the material to transfer electric current
- Usable Magnetic Field: Amount of magnetic field accessible or useful to core expansion

- Dimensions: Amount of space that the component will use
- Heat Dissipation: Ability of the component to release heat
- Weight: Potential weight of the component
- Cost: Potential price of the component

4. Selected Components

The components used in the final design were selected based off of the relevant criteria chosen in *Section 3*. For the power source, a standard wall outlet was used primarily because it is easily accessible, virtually cost free, and provides sufficient voltage for the solenoid. The magnetostrictive core material is pre-specified as Terfenol-D, however, the geometry of the core had different design possibilities. The chosen geometry is a circular rod with a 4in length and a 0.25in diameter. This geometry was chosen to provide a usably stroke distance, while still being relatively inexpensive to manufacture. The housing for the final design is a cylinder made from 2011-T3 aluminum, which is non-magnetic, inexpensive, and strong enough to handle the stresses required for the design. The simplest and most effective hysteresis control system are compressive pre-stress bolts. The bolts are made from brass so that their pre-stress can be easily overcome by the Terfenol-D core. A hydraulic lever system is used because volume manipulation takes up significantly less space than other types of lever systems. Hydraulic levers also have much less innate hysteresis than mechanical levers. The way in which all of the selected components interact has also been considered and tested to ensure that they can function effectively with one another.

5. Proof of Concept

Due to lack of the Terfenol-D core the proof of concept involves only the lever and coil. *Figure 1* shows the proof of concept designs for both the solenoid and the lever system. The lever shown on the right proves that the small stroke can be amplified with a 15:1 lever ratio. With an input of 75μm (0.003in) the lever system is able to output an ending stroke of approximately 1mm (0.045in). The coil consists of magnetic wire with over 1200-1300 turns and a 12V power supply to produce a magnetic field. Proof of the field is demonstrated by pulling small magnetic materials into the center. The magnetic flux density of the magnetic field with a magnitude of 30 mT was produced by a 2A current running through the solenoid.

Figure 1: Proof of concept for the solenoid (left) and micromotion (right)

6. Final Design

Figure 2 depicts a CAD model of the final design of the actuator, which was created in SolidWorks. This model shows the change from the bar lever to the hydraulic chamber to achieve stroke amplification. The purpose of this alteration was to develop a more compact device and reduce mechanical hysteresis.

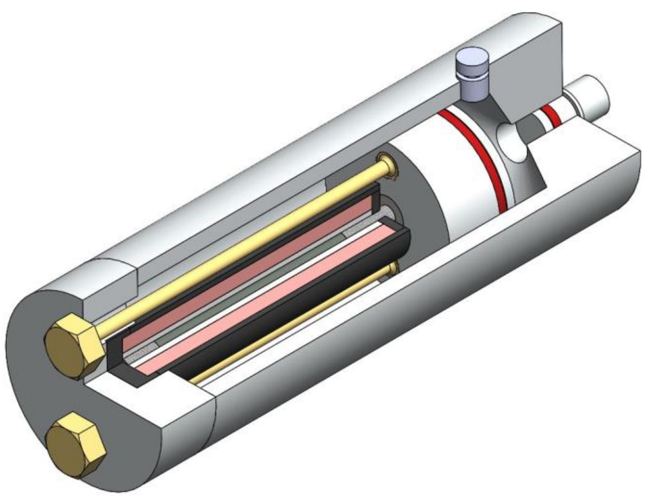

Figure 2: CAD model of final design

7. Exploded View

Figure 3 shows an exploded view of all the components. The Terfenol-D rod is fitted with the iron core stops on both sides. This rod is then slid inside the copper wire solenoid, which is then fitted inside the iron cylinder. The iron cylinder rests on the aluminum endcap shelf, where the pre-stress bolts will then surround the core setup. The large piston is bolted into the core setup to begin pre-stressing the Terfenol-D core. This entire setup is then slid into the aluminum housing where the bleeder valve is placed and the hydraulic chamber is filled. The small piston is the last component to be placed on the device in order to create an airtight fluid chamber.

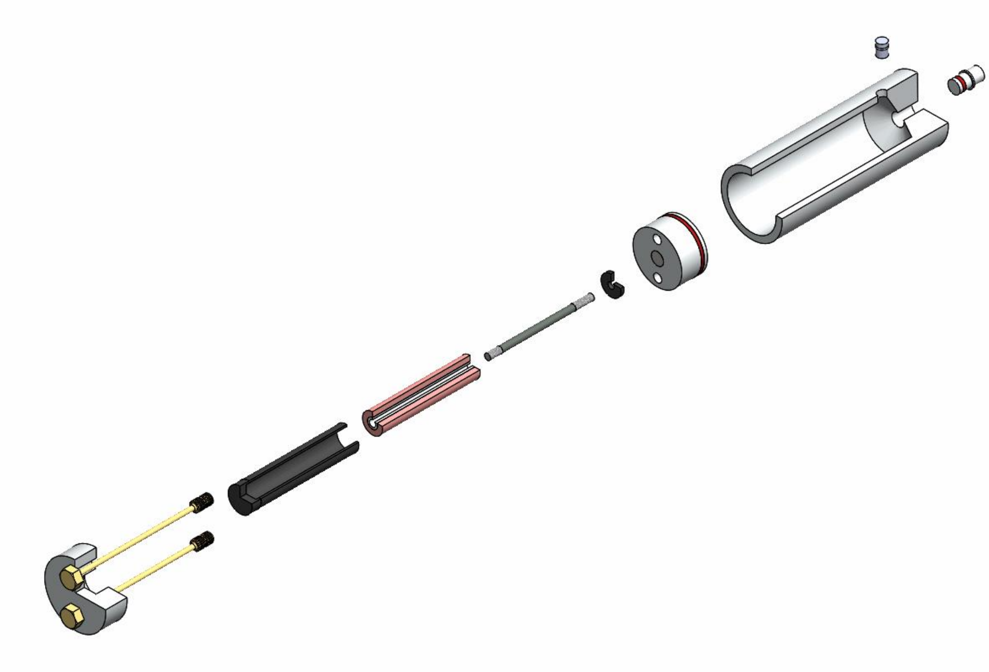

Figure 3: Exploded view of final design

8. Prototype Fabrication

8.1 Housing

The aluminum housing shown in *Figure 4* was the most time consuming part to manufacture, it consumed more aluminum stock than all the other parts combined, and required that most of the interior be removed. The housing incorporates the fluid chamber, and therefore a chamfer is added at the very bottom of the tube where the fluid will reside.

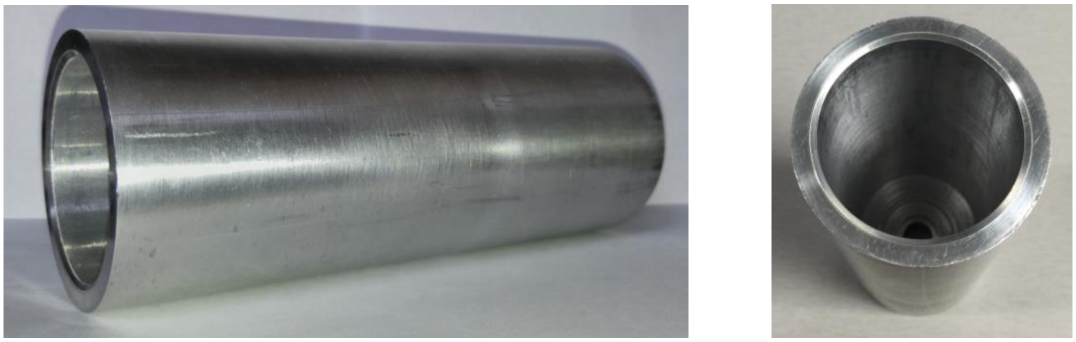

Figure 4: Aluminum housing outer view (left) and inner view (right)

8.2 Pistons

The large piston shown in *Figure 5* fits into the fluid chamber at one end and the small piston from *Figure 5* fits into it at the other end. Both pistons were turned town from the original aluminum stock using a lathe and grooves for the seals have been added. Threaded holes for the bolts on the large piston are also drilled. *Figure 6* shows the steel impact plate which prevents the aluminum from indenting.

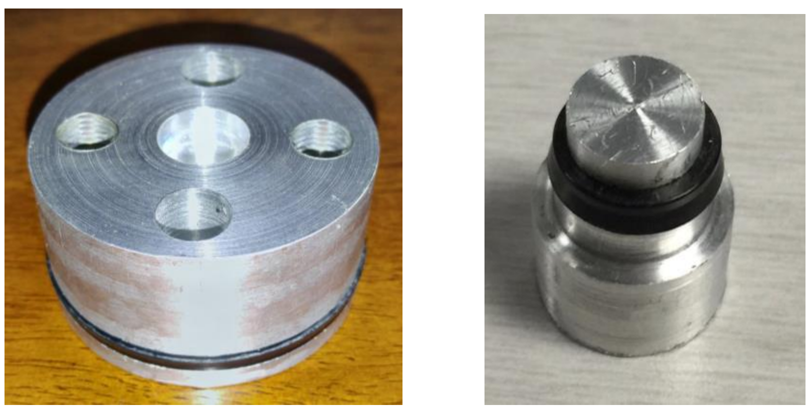

Figure 5: Large aluminum piston (left) and small aluminum piston (right)

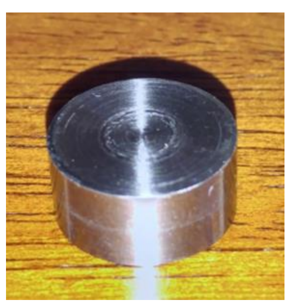

Figure 6: Steel impact plate

8.3 Iron Components

The grade of iron chosen for this design is particularly difficult to machine. Displayed in the right *Figure 7* is the rear iron end cap which was cut from a solid iron rod. In the left of *Figure 7* is the 4in cut iron cylinder that will house the solenoid.

Figure 7: Iron solenoid casing (left) and iron end cap (right)

In order to attach the front iron end cap to the solenoid housing, a heat fitting method was implemented. The solenoid housing was heated until it expanded to a diameter that the end cap could fit within. Once this diameter was achieved, the end cap was clamped into position and the solenoid casing was allowed to cool. The housing and end cap assembly after heat fitting is shown in *Figure 8*.

Figure 8: Front iron end cap heat-fitted in solenoid casing

The iron core stops are shown in *Figure 9*. The purpose of these components is to communicate the elongation of the Terfenol-D to the large piston, transmit the compression of the pre-stress bolts, and complete the magnetic circuit.

Figure 9: Iron core stops

8.4 Aluminum End Cap

The aluminum end cap, shown in *Figure 10*, is made from the leftover stock. While there are overlapping holes they will not be a problem because the bolts are a slightly smaller diameter, leaving clearance between the core and the bolts.

Figure 10: Aluminum endcap

8.5 Bolts

The pre-stress bolts, shown in *Figure 11*, are the most difficult components to manufacture. The threads are 3/8th-24 ANSI inch with a 0.17in diameter.

Figure 11: Brass pre-stress bolts

9. Design Modifications

Alterations to the original design were required in order to resolve mechanical or manufacturing issues. The two main areas for changes are the iron components and the fluid chamber. Smaller components such as the aluminum endplate and the bolts were also altered.

The first iteration of the design made use of four steel bolts. However due to the modulus of elasticity of the steel the bolts do not stretch before the core compresses. To allow the bolts to stretch the material was changed to brass with a smaller diameter. A stainless steel impact plate is added into the large pistons to prevent indentation of the aluminum. An iron washer was heat fit into the iron cylinder to ensure constant contact between the iron components. The iron cylinder assembly was moved inside the endcap for support.

The fluid chamber was changed from a 45° to 60° chamfer to increase ease of manufacturability. This does not affect the stroke amplification. A bleeder valve was inserted into fluid chamber to allow the chamber to be sealed without any air bubbles.

10. Completed Prototype

All of the components that precede the small piston will be combined together before being inserted into the fluid chamber. The partially complete assembly of these inner components is shown in the left of *Figure 12*, with the total assembly shown on the right.

Figure 12: Inner core assembly (left) and full assembly (right)

11. Performance Testing and Results

The individual components of the prototype were tested before assembly in order to verify all components would function together properly. Testing included solenoid electrical testing to verify calculated values of voltage, amperage, and resistance, as well as magnetic field generation, thermal testing using ANSYS APDL to find potential and maximum temperatures and temperature distribution given steady-state conditions, elongation tests for the Terfenol-D with and without pre-stress, and finally testing that verified the stroke amplification utilizing the hydraulic lever system.

11.1 Solenoid Electrical Testing

The team calculated electrical values based on using a wall outlet power source of 120VAC, and 94 ohms, with 1.2 amps through the solenoid to generate the magnetic field. The measured values found during testing were 125VAC through the wall outlet, 96 ohm resistance through the solenoid, and 0.72 amps of current running through the solenoid. While the voltage and resistance were similar to the calculated values, the current was nearly half of what we expected. The 0.48 amp difference in the current was caused by impedance and eddy currents in the solenoid, as the values calculated did not account for AC electrical losses or the effect of resistance increasing with temperature.

11.2 Solenoid Magnetic Field Generation

The magnetic field generated by the solenoid was measured using a Gauss meter, which was placed at the center of the solenoid, where the Terfenol-D would be placed. The calculations yielded a result of 107.5mT minimum magnetic field. The Gauss meter measured a magnetic field of 153mT. The difference between the calculated and measured values was expected, because the iron casing and core stops used to complete the magnetic circuit concentrate the magnetic field, and the calculated value was a minimum value, rendering our measured value acceptable.

11.3 ANSYS Thermal Testing

Figure 13 shows the results of the ANSYS APDL thermal testing. This test showed that, with the maximum temperature achievable by the solenoid given the electrical parameters, the temperature experienced by the system was 106℃, which is still within an acceptable range, and the heat quickly dissipates, utilizing the aluminum endcap as a heat sink, directing it away from the more sensitive components.

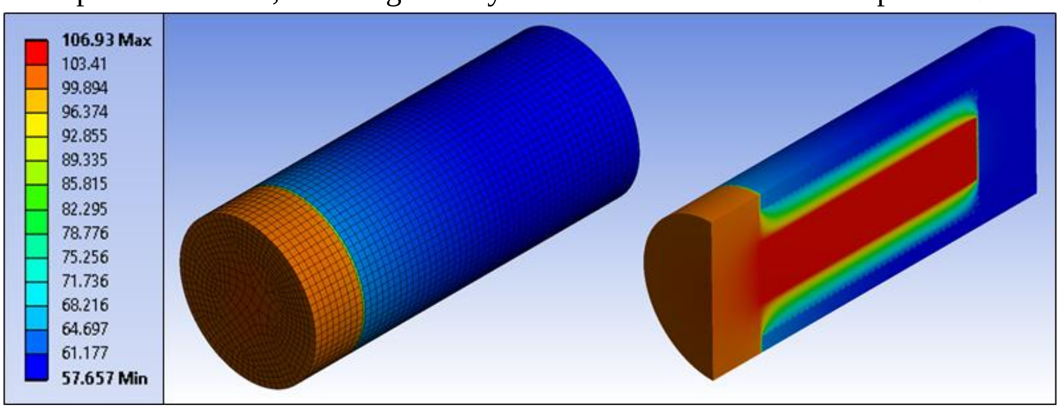

Figure 13: ANSYS Temperature Distribution

11.4 Stroke Output Testing

3 tests were completed to test the stroke output testing. Each test was performed using the 125V AC power supply. The three different tests are listed as follows using a digital multimeter indicator accurate to 1 micrometer. Table 2 displays the results of each test.

1. No loads applied: This test was done by applying a magnetic field to the Terfenol-D core to measure the pure elongation without the bolts causing pre-stress.

2. Loads applied: With the magnetic field applied to the Terfenol-D core the stroke is measured with the pre-stress bolts and large piston attached.

3. Total device output: This test was completed using the full device, including the stroke amplification fluid chamber.

Table 2 - Results

Test Type	**Approximate Output Stroke (µm)**
No loads applied	30
Loads applied	60
Total device output	960

From the total device output test and the loads applied test the total lever ratio remains the calculated 1:16, which was above the consultation of 1:10.

12. Recommended Alternatives to Design

There are several alternatives to this design that the team would like to recommend. These involve changes to the hydraulic chamber and the pre-stress bolts. The recommended changes are listed as followed:

1. Using cenospheres in lieu of hydraulic fluid in the chamber: Cenospheres are microscope, hollow, ceramic spheres that look like a powder. These spheres are made of mostly silica and alumina, and are self-lubricating. These cenospheres can be a beneficial addition to the design if they are proven to act as an incompressible fluid. If these spheres do act as such, they would be able to operate in the high altitude that airplanes are subjected to without expanding like the current hydraulic fluid. With this first recommendation comes the second: implementing an hourglass shaped chamfer in the fluid chamber as opposed a linear chamfer. This gradual change would allow the cenospheres to flow much smoother as opposed to the linear chamfer currently in the design.

2. Replace pre-stress bolts with elastic cables: By replacing the pres-stress bolts with an elastic cable, the stress placed on the Terfenol-D rod could be measured easier than with the current bolts. This change would also decrease manufacturing costs and efforts, as the current pre-stress bolts are difficult to fabricate due to their uncommon and irregular shape.

3. Potential use of Terfenol-D powder infused ferrofluid: This design alternative is an idea for a future experiment using Terfenol-D powder infused in a ferrofluid. This alternative would depend on how the ferrofluid would act when an external magnetic field is applied. If the fluid volume expands with the magnetic field, then this fluid can take the place of the solid Terfenol-D rod.

4. Use a direct current power source: Converting the power source from AC to DC power would allow for a stronger magnetic field to be applied. With a stronger magnetic field, more elongation is experienced, meaning more stroke magnification can be applied. The difficulty with this recommendation is the potential safety problem in using DC power.

13. Bill of Materials

The bill of materials shown in *Table 3* outlines all of the material and components purchased for the prototype. Additional expenditures not listed include the cost of shipping, manufacturing, taxes, and other equipment and materials purchased for testing.

Table 3: Bill of materials

Item	Individual Cost ($)	Quantity	Total Cost ($)
Aluminum	41.52	2	83.04
Iron Tube	138.00	1	138.00
Iron Rod	171.00	1	171.00
Solenoid	790.00	1	790.00
Brass	10.97	1	10.97
Terfenol-D	447.00	1	447.00
Large Seal	5.56	1	5.56
Small Seal	3.94	1	3.94
Brake Fluid	9.95	1	9.95
Total Cost*			1672.01

14. Conclusions

The Northern Arizona University Magnetostrictive Actuator capstone team completed a functional prototype of the proposed device. All components have been manufactured and tested. Several complications arose with the manufacturing of parts that resulted in setbacks. Additional setbacks included substantial lead times, and adjustments for ease of assembly. The appropriate calculations have been conducted to avoid plastic deformation and reduce heat transfer to undesirable areas. The project has stayed well within budget, consuming under half of the available funding. There are several potential improvements that could be implemented for future iterations of the design. These improvements are discussed in detail in *Section 12*. Throughout production of the design, contingency plans were generated for numerous scenarios to ensure that setbacks were resolved as soon as they occurred.

All of the primary constraints were exceeded, including 30lb output force, 0.04in output stroke, 1:16 lever ratio, and the device dimensions fit well within the specified 3x5x12in^3 volume requirement. With a total material cost of about $1700, the HEM actuator may be a viable replacement for the current valve systems currently in use by Honeywell. One of the proposed design changes involving cenospheres (discussed in *Section 12*) will also make this design suitable for high temperature applications.

15. Acknowledgments

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Honeywell Contacts

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