A NEW MAGNETOELASTIC FORCE TRANSDUCER

E. E. Mitchell

U. S. Naval Academy
Systems Engineering Department
Annapolis, Maryland 21402

ABSTRACT

This paper describes a magnetoelastic based force transducer, one that may be used in the manner of a standard strain gage. The sensor appears to offer several advantages over resistance and semiconductor strain gages. In particular, it has a sensitivity more than an order of magnitude greater than semiconductor strain gages.

I. INTRODUCTION

The purpose of this paper is to present a new transducer or sensor design that is currently under study. The sensor study was instigated along with robotic wrist design at the Naval Surface Weapons Center (NSWC) at White Oak, MD. The work has continued under the auspices of the National Bureau of Standards, Automated Machinery Division, Gaithersburg, MD.

The basic problem was to provide a more sensitive measurement of forces and torques in a robot wrist. The objective being to produce better feedback signals for intelligent robotic operations. In order to help understand the operation of the transducer, a brief discussion of the background of the material and material properties are presented first. Following that is a description of the sensor operation and then the resulting performance.

II. BACKGROUND

The sensor operates because of a material property called magnetostriction. While this is a troublesome property for a transformer core material to possess, there are applications in which it is a useful feature. The material also exhibits the Villari Effect, where physical changes, such as changes in stress are accompanied by changes in the material magnetic properties.

The sensor is designed around a relatively new material called Metglass. The name is derived from the fact that the material is metallic in composition, but has some of the physical properties of glass. The material comes in the form of a ribbon and is highly magnetic. At present there are three groups of amorphous materials [1]. One group, based on cobalt,

display almost no magnetoelastic effects. Applications of this group include 400 Hz transformers, switching power supplies, magnetic heads and variable delay lines. One of the first prototype applications of the ribbons was magnetic shielding. Because the ribbons can be woven and braided, they have been used for cable shielding and other types of flexible shielding wraps [2].

A second group of amorphous materials are the magnetoelastic Fe group. In addition to their magnetic properties, they have very good mechanical elastic properties. Since they are amorphous, there are no grain boundaries and no slipping of crystalline surfaces. Hence, the ribbons can stand greater stress and plastic deformation than standard crystalline ferromagnetic compounds [3]. These ribbons have been used in force sensors [4,5,6], extensometers [3] and non-touching torque sensors [7,8].

One of the main differences in the amorphous materials and the normal Fe crystalline compounds is the magnetization process. In the amorphous materials, magnetization takes place through domain rotation rather than through domain wall displacement [1,2,9]. This results in low losses and linear hysteresis curves [1,9].

There have been a series of new compositions over the last few years. In addition to the advances made in basic material composition, the magnetic properties may be changed and improved through several annealing processes [1,10]. Heat treating in a magnetic field allows one to shape the hysteresis curve for different applications. A recently reported application of magnetoelastic ribbons to a torque transducer used heat treating to stress relieve the ribbons and improve sensor performance [8]. Mori built one of the first force transducers and used mechanical annealing in addition to heat treatment [3].

Magnetoelastic ribbons offer several advantages over standard strain gages. First, they have the potential to be orders of magnitude more sensitive than strain gages. They have a higher temperature stability than even resistance gages, a higher maximum operating temperature and a greater linearity [3]. On the other hand, they may need shielding, sometimes when annealed the ribbons become brittle and long term time effects are not known.

The actual material property that changes in the ribbons is the susceptibility, χ . Figure 1 is a plot of inverse susceptibility versus stress for a 2605SC ribbon [10]. As the figure illustrates, a very linear relationship exists. Although the material property that changes is susceptibility, in general one must measure some other parameter. Inductance is one of the obvious choices.

III. BASIC SENSOR OPERATION

Figure 2 illustrates the basic sensor design, consisting of a Metglas ribbon bonded to a base material with a coil wound around the assembly. A change in stress in the base material is transmitted to the ribbon. This causes a change in ribbon susceptibility and hence a change in the coil inductance. If the coil is connected in the feedback loop of an operational amplifier, as shown in Figure 3, then this change in inductance is measurable.

Using linear system theory, the coil may be represented by a lumped impedance Z , as

$$Z = R + j\omega L \quad (3.1)$$

where R is the dc resistance, L the inductance of the coil, and ω is the radian excitation frequency. The output e_2 is used as a reference. This allows e_1 and e_2 to be compared, resulting in a measurable change in magnitude and phase shift.

A Metglas ribbon was bonded to a piece of standard aluminum bar stock, as in Figure 2. As temperature increased, the aluminum bar expanded, which in turn stressed the Metglas ribbon. Figure 4 is a plot of the measured change in impedance, ΔZ as a function of change in temperature of the aluminum bar. The slope of the line was found to be

$$\frac{\Delta Z}{\Delta F} = 1.1 \frac{\Omega}{^\circ F} \quad (3.2)$$

The coefficient of expansion of the aluminum bar is one of its standard specifications, from it one may write

$$\frac{\Delta \epsilon}{\Delta F} = 11.6 \frac{\mu \epsilon}{^\circ F} \quad (3.3)$$

If equations (3.2) and (3.3) are combined, the result is

$$\frac{\Delta Z}{\Delta F} = 94.3 \frac{m\Omega}{\mu \epsilon} \quad (3.4)$$

where $m\Omega$ represents milliohms and $\mu \epsilon$ represents microstrains.

Equation (3.4) is a measure of the sensitivity of the Metglas sensor and will be compared to that of a standard resistance strain gage next.

IV. FIGURE OF MERIT

The term gage factor was defined for resistance type strain gages as

$$G_{sg} = \frac{\Delta R/R_0}{\Delta \epsilon} \quad (4.1)$$

where R_0 is the nominal gage resistance and ΔR is the change in resistance due to the change in strain, $\Delta \epsilon$. A typical resistance strain gage has a gage factor of 2 and an R_0 of 120 ohms.

A semiconductor strain gage is constructed of strain sensitive material, such as silicon [11]. These devices also undergo a change in resistance due to a change in strain, hence the gage factor of equation (4.1) applies to them as well. Typical gage factors for semiconductor gages are on the order of 100.

If equation (4.1) is solved for $\Delta R/\Delta \epsilon$, where $R_0 = 120$ ohms and $G_{sg} = 2$, then a measure of the sensitivity of a standard, resistance type strain gage is

$$\frac{\Delta R}{\Delta \epsilon} = 0.252 \frac{m\Omega}{\mu \epsilon} \quad (4.2)$$

If equations (3.4) and (4.2) are compared, the difference is noticeable. They indicate that the Metglas sensor is many times more sensitive than a standard resistance strain gage.

Given a sensor configuration built as the one illustrated in Figure 2, the dc resistance of the coil may be measured. If the nominal value of Z is defined as this dc resistance, Z_0 and if a figure of merit is defined which has the same form as equation (4.2), then a measured result is

$$F = \frac{\Delta Z/Z_0}{\Delta \epsilon} = 1450 \quad (4.3)$$

Note that this indicates that the Metglas sensor is an order of magnitude more sensitive than even the semiconductor strain gage.

There is some hesitancy to call the figure of merit in equation (4.3) a gage factor. The gage factor equation is defined in terms of the strain gage physical parameters, i.e., resistance and change in resistance due to change in physical dimensions. Equation (4.1) does not include the electronics or any signal processing. On the other hand, equation (4.3) is based on derived parameters, that is, impedance change as a function of change in the physical parameter susceptibility. However it is labeled, the factor of 1450 is what is currently being measured and used, not what is possible.

The parameter that is being measured in the current sensor configuration is the inductance, L . If a figure of merit were defined using measured values of inductance, it would have the form

$$F = \frac{\Delta L/L_0}{\Delta \epsilon} \quad (4.4)$$

where L_0 is the initial, or inductance in the unstressed sensor and ΔL is the change in inductance due to a load change.

A sensor was mounted on a bar and measured in both tension and torsion modes. The measured figure of merit was found to be 2223 and 2355 respectively. This is a typical value of the general magnitude found for several sensors.

Savage and Spano [10] worked out a theoretical value of the figure of merit for the 26055SC Metglas ribbon, based on susceptibility changes. Their figure of merit is defined as

$$F = \frac{\Delta \chi/\chi}{\Delta \epsilon} \quad (4.5)$$

where χ is the material susceptibility, and their results are shown in Figure 5. Note that the figure of merit is also a function of the intensity of the driving field.

V. RESULTS

There are many factors that affect the performance of the Metglas sensor, just as there must have been many factors affecting the performance of strain gages when they were first developed. As Figure 5 illustrates, it appears that the greater the intensity of the driving field, the less the sensitivity of the sensor. On the other hand, the larger driving field produces larger output signals which require less amplification.

The bonding of the sensor to the base material is the most critical factor in the process. Any operation that affects or reduces the domain rotation of the Metglas ribbon reduces its sensitivity. This would imply that a perfect bond between the sensor and a base material would so restrict domain rotation that the sensor would not work. For one sensor, and only one, using equation (4.4), the figure of merit has been measured in excess of 7000. As mentioned previously, the typical value is on the order 2500.

Because of the extremely high sensitivity and the electronics, the Metglas sensor has a much larger output than a standard strain gage. Very little amplification is required to achieve output signals of ± 1 volt magnitude.

Figure 6 illustrates an output for small strains and Figure 7 illustrates an output for larger strains. The sensor of Figure 7 was driven with a larger signal and had an overall gain unity. It is felt that the nonlinearity can be removed, but no attempt to do so has been made to date.

As the data illustrates, the current version of the sensor is demonstrating the ability to be about 2 order of magnitude more sensitive than standard strain gages. In addition, it appears to have the potential of much better performance.

ACKNOWLEDGEMENTS

This work was supported by the National Bureau of Standards, Automated Manufacturing Division, Washington, D.C.

†Metglas is a registered trademark of Allied Chemical Company.

REFERENCES

- [1] Boll, R. and Warlimont, H., "Applications of Amorphous Magnetic Materials in Electronics," *IEEE Trans. Mag.*, Vol. 17, No. 6, Nov 1981.
- [2] Warlimont, H. and Boll, R., "Applications of Amorphous Soft Magnetic Materials," *Journal of Magnetism and Magnetic Materials*, Vol. 26, March 1982.
- [3] Mohri, K., and Sudoh, E., "New Extensometers Using Amorphous Magnetostrictive Ribbon Sound Cores," *IEEE Trans. on Magnetics*, Vol. 17, No. 3, May 1981.
- [4] Mohri, K., and Korekoda, S., "New Force Transducers Using Amorphous Ribbon Cores," *IEEE Trans on Magnetics*, Vol. 24, No. 5, Sep 1978.
- [5] Mohri, K. and Sudoh, E., "Sensitive Force Transducers Using a Single Amorphous Core Multivibrator Bridge," *IEEE Trans. Magn.*, Vol. 15, No. 6, Nov 1979.
- [6] Meydan, T. and Overshott, K. J., "Amorphous Force Transducers in ac Applications," *J. Appl. Phys.*, Vol. 53, No. 11, Nov 1982.
- [7] Harada, K., Sasaa, I., Kawajiri, T. and Inoue, M., "A New Torque Transducer Using Stress Sensitive Amorphous Ribbons," *IEEE Trans. Magn.*, Vol. 18, No. 6, Nov. 1982.
- [8] Sasada, I., Inoue, M., Hiroike, A., and K. Harada, "A New Method of Assembling a Torque Transducer By The Use of Bilayer-Structure Amorphous Ribbons," *IEEE Trans. Magn.*, Vol. 19, No. 5, Sept 1983.
- [9] Spano, M. L., Hathaway, K. B. and Savage, H. T., "Magnetostriction and Magnetic Anisotropy of Field Annealed Metglas 2605 Alloys via dv M-H Loop Measurements Under Stress," *J. Appl. Phys.*, Vol. 53, No. 3, March 1982.
- [10] Savage, H. T. and Spano, M. L., "Theory and Application of Highly Magneto-elastic Metglas 2605SC," *J. Appl. Phys.*, Vol. 53, No. 11, Nov 1982.
- [11] Charkey, E. S., *Electromechanical System Components*, Wiley, 1972.

Figure 1 Inverse Susceptibility vs. Strain

Figure 2 Basic Sensor Design

Figure 3 Basic Op-Amp
Signal Detector

Figure 4 Change in Impedance with Temperature

Figure 5 Figure of Merit

Figure 6 Strain vs. Load

Figure 7 Millivolt Output vs Load