Development of Low Volume Shape Memory Alloy Variable Ballast System for AUV Use

Dr. Graeme J Rae
Ocean Engineering Program
Division of Marine and Environmental Systems
Florida Institute of Technology
150 West University Boulevard
Melbourne, FL 32951
Tel: (407) 674 7244
Fax: (407) 674 7212
email: graeme@marine.fit.edu

AWARD #: N000149810134

http://www.marine.fit.edu/serl

LONG TERM GOAL

The long term goal is to develop a near silent, air free, electrically operated ballast system for use in underwater vehicles.

OBJECTIVES

Arrive at a workable design for a ballast system that decreases and increases buoyancy at a range of depths, in increments small enough for precise control. It would operate on command, silently, electrically, controllably, and without release of any material or air.

Examine how the fabrication and shape memory training methods effect each other for the different actuator designs.

Operate and test actuators for system performance: buoyancy to volume ratio, life cycle performance, fatigue, response speed, power consumption, robustness, reliability, depth, etc.

APPROACH

The basic concept is that a shape memory alloy (SMA) will enclose a small volume of air or vacuum. The transformation of the shape memory alloy between crystalline phases effects a transformation between two shapes. If these shapes are selected so as to enclose different volumes, then the volume enclosed by the shape memory alloy--and thus its wet displacement--will change when they do. (see figure 1) By splitting the enclosed volume among many identical elements, we achieve robustness to imprecise design/manufacturing or material failures. Also any number of the individually sealed elements can be used to fill whatever volume is required providing great design flexibility.

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The theoretical maximum performance was calculated on the following basis. First, the required volume of shape memory alloy material was determined by comparison of its maximum recoverable strain energy with the energy required to pull a vacuum in a given volume at various depths. Then the shape memory alloy volume was compared with the given evacuated volume to arrive at a ratio of the buoyancy (from the evacuated displacement), and the total displacement of the system.

The design challenge consists of selecting 2 shapes in which those components of the hydrostatic pressure-induced stresses that are aligned against the recovery motion, do not exceed the shape memory alloy's recovery stresses.

Operation at greater depths require thicker-walled elements, which take up more space and add weight. This requires more foam volume for the system to achieve neutral buoyancy in rest mode, so the ratio of variable buoyancy to total system volume decreases.

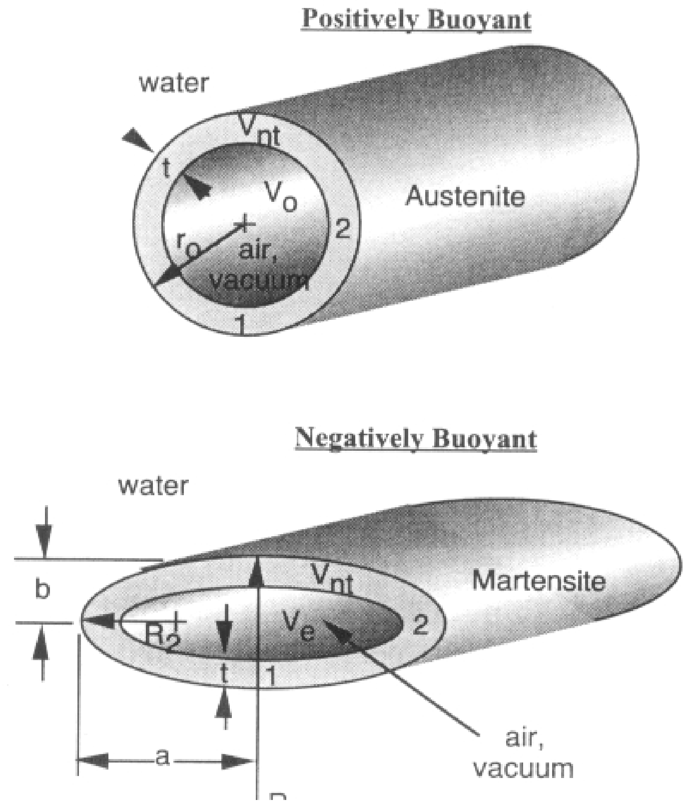

Figure 1

The simplest design scheme uses hollow straws as the buoyant elements. These straws squash flat into ellipses (in cross section) to lose buoyancy, and recover to round cylinders to gain buoyancy. Recovery stress acts to bend sections of the cross section when translating between shapes. Performance calculations are completed for this basic collapse mode. Other collapse modes and element shapes give more favorable mechanical advantages to the working cross-section, allowing operation at greater depths.

Pre-pressurizing the air inside the element, and different element arrangements can extend the depth range also. Performance is also completely independent of vehicle and device size, so the concept is especially suitable for miniaturization.

The trim ballast actuator requires the 2-way shape memory effect to decrease buoyancy at the surface and increase it at depth. Recoverable strain is then limited to about 4%. The operating depth is limited by the recovery stress acting on the collapsed shape.

WORK COMPLETED

Verification of original mathematical model of SMA behavior using Finite Element Methods.
The FEM package initially used was incapable of modeling the straws with any degree of accuracy as it was limited in the number of elements. Subsequent models should prove more realistic. However the FEM model did verify the overall shape change characteristics developed in the original research [1] although deflection as a function of strain did not match. Extensive results of this work can be found in [2]

Development, design and construction of two way training system.
In order for a SMA to undergo a repeated shape change it must be trained by being constrained in one shape while being repeatedly heated and cooled above and below its transition temperatures. In addition the deflection and deforming stress must be measured and accurately repeatable. A general layout of the training set up is shown in Figure 2.

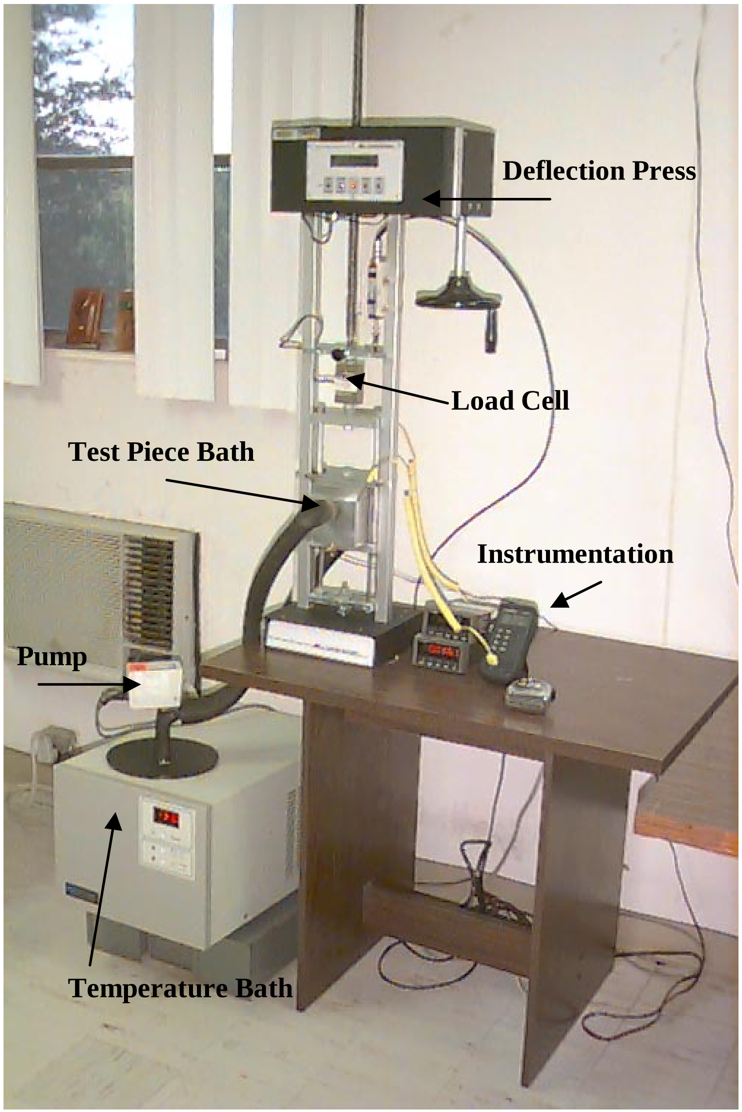

Figure 2

Determination of optimal straw dimensions.
Many possible straw configurations were allowable according to the performance characteristics determined both by mathematical and FEM modeling. The final decision of 0.25” OD and 0.01” wall thickness was chosen for convenience and due to the fact that these dimensions lie in the middle of the performance window of SMA ballast systems. No SMA tubes are manufactured with such a small thickness to diameter ratio however and will have to be custom made.

RESULTS

Theoretical Assessment of VBS performance
The major result is a theoretical assessment of VBS performance. By considering the maximum allowable recoverable strain, and by examining the geometric and kinematic properties of the two phases of the VBS It has been determined that the net result of these several factors is a performance close to the 235 kg force/m^3 at 20 to 30 atmospheres requested by a previous BAA. This shows that the system will be suitable for inclusion in

small, near neutral vehicles and is ideal for trim control. The excessive cost of SMAs is likely to preclude its use as main ballast systems or in large vehicles.

Operation of Training System

The training apparatus has been operated at temperature ranging from -52• C to 85• C in an ambient temperature of approximately 26• C. However the times taken to achieve these extremes were too long to be of use in an actual training procedure. Temperature cycling between -30• C and +50• C are felt to be sufficient for training purposes in which case cycles times are in the order of a few minutes.

Straw Training

No SMA straws have been tested due to problems in their manufacture. The alloys are extremely exotic and the dimensions of 0.25” diameter with wall thickness of 0.01” required custom manufacture. These straws are now being manufactured and should undergo training sometime early in 1999.

IMPACT/APPLICATIONS

The impact of this work if successful is in the area of small, underwater vehicle trim control. The approach negates the need for bulky, noisy and complex air based ballast systems. Many small underwater vehicles such as AUVs, Slocum Gliders, SDVs ROVs, and Submarine Decoys are prevented from using a trim ballast system due to constraints on noise production, available onboard power or size constraints. This work will help solve many of these problems.

TRANSITIONS

The work is being closely followed by the 21” UUV group at Naval Underwater Warfare, and also the Advanced Marine Systems Laboratory at Florida Atlantic University.

REFERENCES

[1] J. McCanna “Theoretical Assessment of Applying Intelligent Materials to Sub Sea Robotics”, Masters Thesis, Florida Institute of Technology, March 1998
[2] G. Siappas “Design and Setup of Training Apparatus for two-way Actuation of Shape Memory Alloy Tubing”, ”, Masters Thesis, Florida Institute of Technology, December 1998

PUBLICATIONS

G.J.S. Rae, J. McCanna. "Shape Memory Alloy Buoyancy Regulator for Subsea Robots." Proceedings of the Ninth Unmanned, Untethered, Submersible Technology Conference. Durham NH. (October 1997).

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PATENTS

“Buoyancy System for Application to Submersible Bodies:” Patent applied for September 1998, Sankey & Luck, Attorneys.