HIGHLY-COMPACT SMA ACTUATORS
A Feasibility Study of Fuel-Powered and Thermoelectric SMA Actuators

1. Objectives

The main goal of this project is to perform a feasibility study on Fuel-Powered and Thermoelectric Shape Memory Alloy (SMA) actuators to develop highly-compact SMA actuators. The specific objectives for the Fuel-Powered Compact (FPC) SMA actuator are given below:

- Design, fabricate and test highly compact Shape-Memory-Alloy (SMA)-based actuators that utilize the high energy density of fuels.
- Optimization of FPC-SMA energy density, compactness and volumetric efficiency. Comparison with conventional actuator systems.
- Implement modular design to allow for alternative energy sources including parasitic heat and electric systems.

The objectives for the Thermoelectric Compact SMA Actuator (TEC-SMA) are given as:

- Develop a Solid State TEC-SMA utilizing the Peltier effect.
- Optimization of TEC-SMA output energy density, output power density and compactness.
- Increase the bandwidth of SMA based actuators.

2. Significance

The prototype design-fabrication-testing process will result in detailed feasibility assessment and quantification of the operational specification ranges for both actuators. The actuators' potential for compactness and miniaturization will be assessed and quantified. The proposed actuator design will merge the advantages of SMAs, fuels and thermoelectric elements, i.e., the high actuation forces, the large power densities and the silent actuation characteristics of SMAs, the large energy densities of fuels and the compactness and operation simplicity of thermoelectric elements.

3. Methodology and Preliminary Results

The approach followed for the development along with the preliminary results for two compact SMA actuators is discussed in the following two subsections.

3.1. Fuel-Powered Compact (FPC)-SMA Actuator

3.1.1. Performance and energy density analysis

Figure 1 shows three possible energy sources and respective SMA actuator systems. The results of the comparison in terms of energy and power density for the systems represented in Figure 1 along with electromechanical and linear motor actuators, with batteries as their power source, have been tabulated in tables 1 and 2. The results have been tabulated for different cases of actuation cycle number (1000, 10,000 and 100,000 actuation cycles).

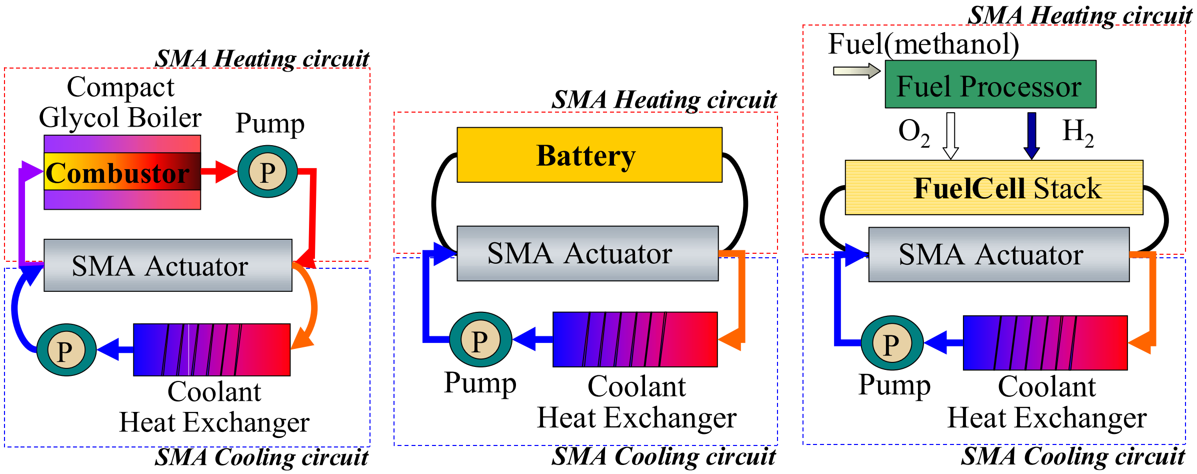


Figure 1. Compact Actuator Systems with fuel+combustor, battery and fuelcell as energy source.

Table 1. Energy Density (Total Mechanical Work/Mass of System)

Actuator Systems	*1,000 Cycle*	*10,000 Cycle*	*100,000 Cycle*
SMA-Combustor	9.887(Wh/kg)	71.04(Wh/kg)	193.6(Wh/kg)
SMA-Battery	4.052(Wh/kg)	4.89(Wh/kg)	4.994(Wh/kg)
SMA-Fuel Cell	0.7605(Wh/kg)	7.038(Wh/kg)	41.1(Wh/kg)
Electromechanical-Battery	2.058(Wh/kg)	16.51(Wh/kg)	55.38(Wh/kg)
Linear Motor- Battery	2.456(Wh/kg)	18.97(Wh/kg)	57.9(Wh/kg)

Table 2. Power Density (Total Mechanical Work/(Mass of System × Cycle))

Actuator Systems	*1,000 Cycle*	*10,000 Cycle*	*100,000 Cycle*
SMA-Combustor	35.59(W/kg)	25.57(W/kg)	6.971(W/kg)
SMA-Battery	14.59(W/kg)	1.76(W/kg)	0.1798(W/kg)
SMA-Fuel Cell	2.738(W/kg)	2.534(W/kg)	1.48(W/kg)
Electromechanical-Battery	7.41 (W/kg)	5.942(W/kg)	1.994(W/kg)
Linear Motor- Battery	8.841(W/kg)	6.829(W/kg)	2.084(W/kg)

The comparison of energy and power densities of generic electromechanical actuator systems, with batteries as energy sources, is based on generic commercial products. These actuator systems showed better energy and power densities than the SMA-Battery and SMA-Fuel Cell actuator system, but significantly less than the SMA-Combustor actuator system.

3.1.2. Conceptual design and preliminary results

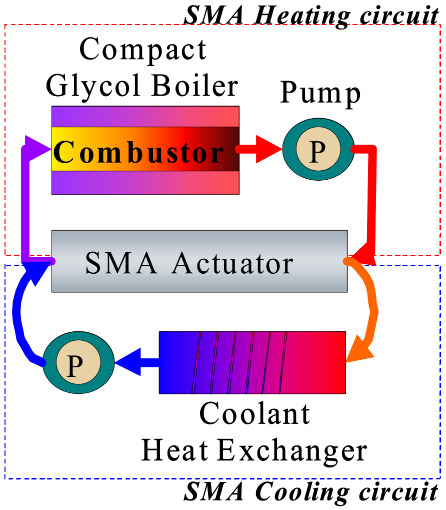
Based on the preliminary analysis, a two phase approach has been followed for the FPC-SMA actuator. The initial phase or phase I of the project involves development of a scaled up model to validate the principal of fuel-powered SMA actuator.

Phase I

The major tasks included in the Phase I of this project are as follows:

- Assembly and Preliminary Tests
- Instrumentation
    - Flow Rate, Temperature, Force and Strain
- Parametric Studies
    - Force, Stroke, Efficiency and Frequency
- FPC-SMA System Characterization
    - Output Energy Density
    - Output Power Density

The proposed principal of FPC-SMA system is shown in Figure 2. Figure 3 shows the phase I FPC-SMA system with improved circulation. The preliminary design parameters for the phase I FPC-SMA actuator are tabulated in Table 3.



Components:

1. Combustor
2. Actuator (SMA Strip)
3. Heat Exchanger
4. Pumps & Valves

Figure 2. Proposed Principle of FPC-SMA System.

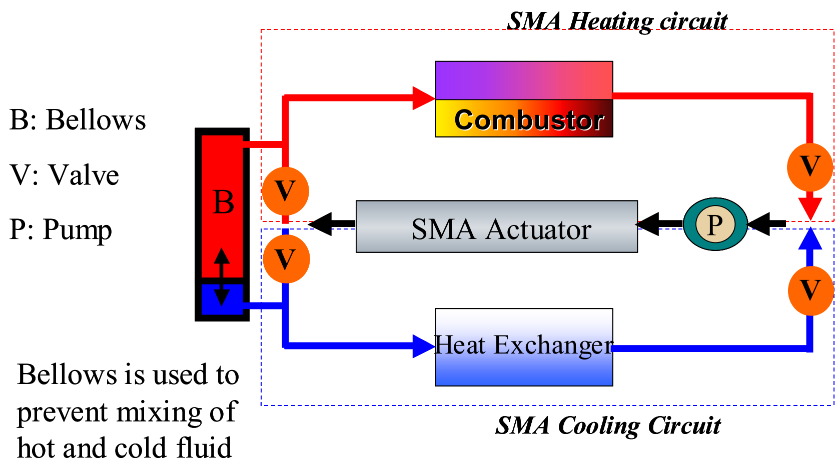


Figure 3. Phase I FPC-SMA System with Improved Circulation.

Table 3. Phase I Design Parameters

SMA Actuation Strain	3%
SMA Strip Dimensions	12mm x 1mm x 254mm
Strip Quantity	4
Actuator Frequency	1 Hz
Operational Stress level	200MPa
Stress Bias Level	100Mpa
Bi-directional Actuation loads	± 1200N
Total bi-directional Actuation loads	± 4800N
Stroke	7.62 mm
Mechanical Stroke Amplification (x10)	76.2 mm, 7.6 cm
Actuation Force after Stroke Amplification	480 N
Stroke Rate	0.1m/s

Figures 4 and 5 show the Phase I experimental setup and the SMA actuator. For an FPC-SMA system without any circulation as shown in Figure 6, preliminary system response results are shown in Figures 6 and 7.

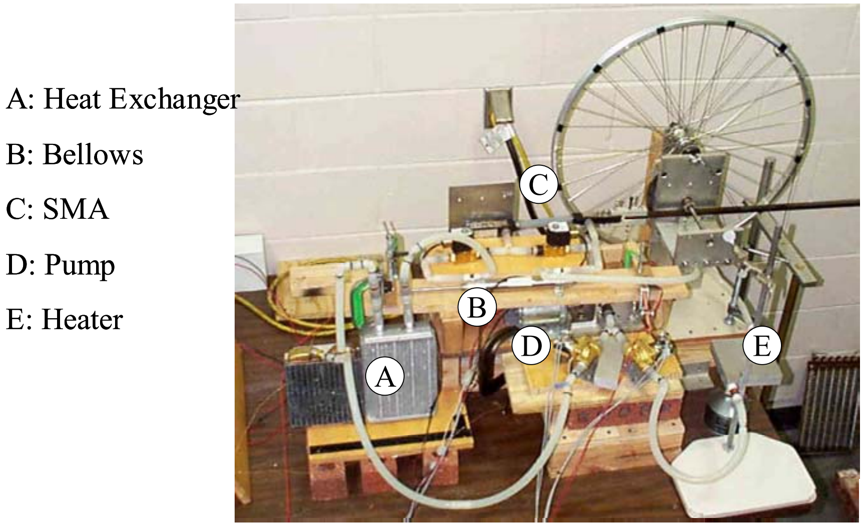
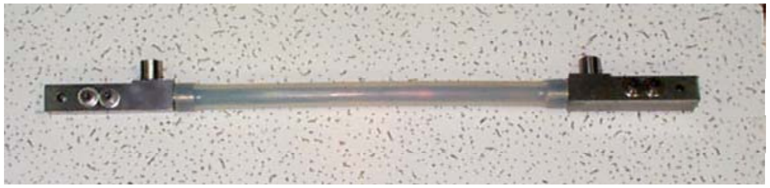


Figure 4. Phase I Experimental Setup.



- 12 mmx0.9 mm SMA Strip
- Silicon Tube for Heating and Cooling Fluid
- Mechanical Connectors

Figure 5. Phase I SMA Actuator.

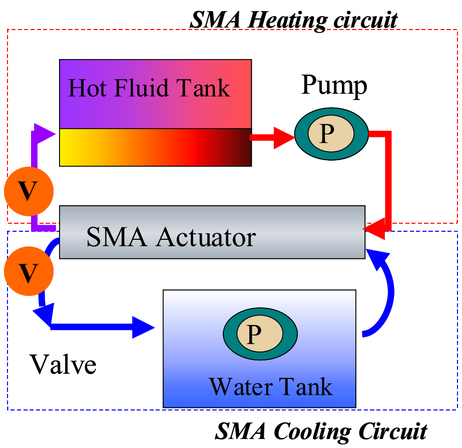


Figure 6. Phase I Open Cycle System.

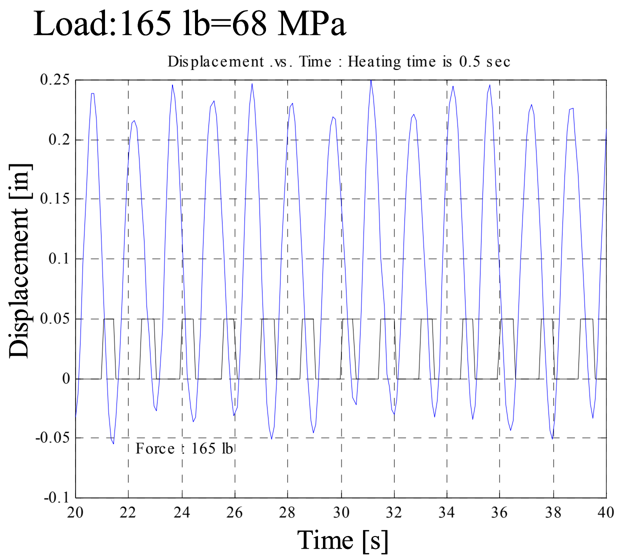


Figure 7. 0.5Hz system response.

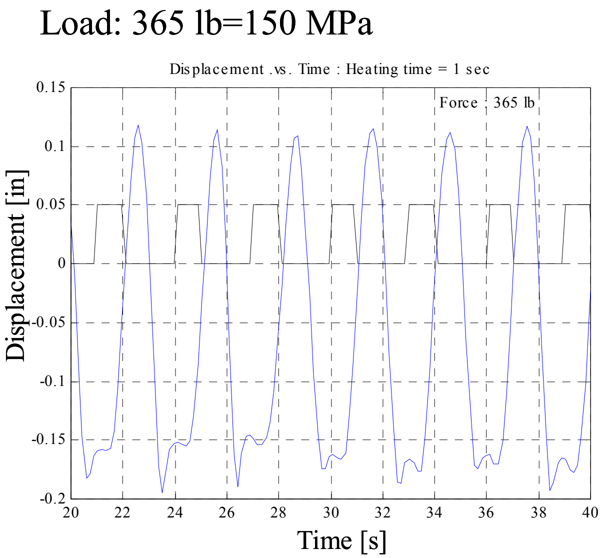


Figure 8. 1.0Hz system response.

Phase II

The phase II of the FPC-SMA actuator project involves the following and is currently under development

- Compactness and Miniaturization Based on Phase I Actuator System.
  - Miniaturization of pump, valves, combustor, heat exchanger, etc.
  - Design and construct a prototype compact actuator.
- Actuator Fatigue Test

Determine the fatigue life of the actuator as a function of actuation stress, strain and frequency.

- Modular Design of Actuator System
  Allows for alternative energy sources

3.2. Thermoelectric Compact (TEC)-SMA Actuator

3.2.1. Conceptual design

The significant benefits of TEC-SMA can be explained as follows

- High Volumetric Efficiency
  Volumetric efficiencies up to 30% higher than electrical motors and up to 4 times higher than hydraulic actuators.
- Actuator Cost
  Simple assembly of final model.
  Low manufacturing and component costs.
  Few moving parts.
- Actuator Life
  SMAs can operate for millions of cycles.
  Thermoelectric elements run without degradation.

Linear, rotary and bimorph actuation modes are being considered for the TEC-SMA as shown in Figure 9. A conceptual design of the TEC-SMA actuator based on different actuation modes is proposed in Figure 10. The pertinent design considerations for the proposed TEC-SMA device are listed as follows:

- Shear Stress at the Thermoelectric SMA Interface.
  A polymer (polyethylene with SiC dielectric) material will be utilized.
- Electrical Isolation of the Electrical Connection.
  The electrical connections will be printed on the polymer surface.
  The polymer strip with the electrical circuit will be easily bonded to the SMA material.
- Manufacturing of a Compact Actuator.
  Etching of electrical print on the polymer and its bonding to the SMA strips will be required.

Similar to the FPC-SMA approach, a two phase development is proposed for the TEC-SMA actuator as well which is currently under development and briefly discussed below.

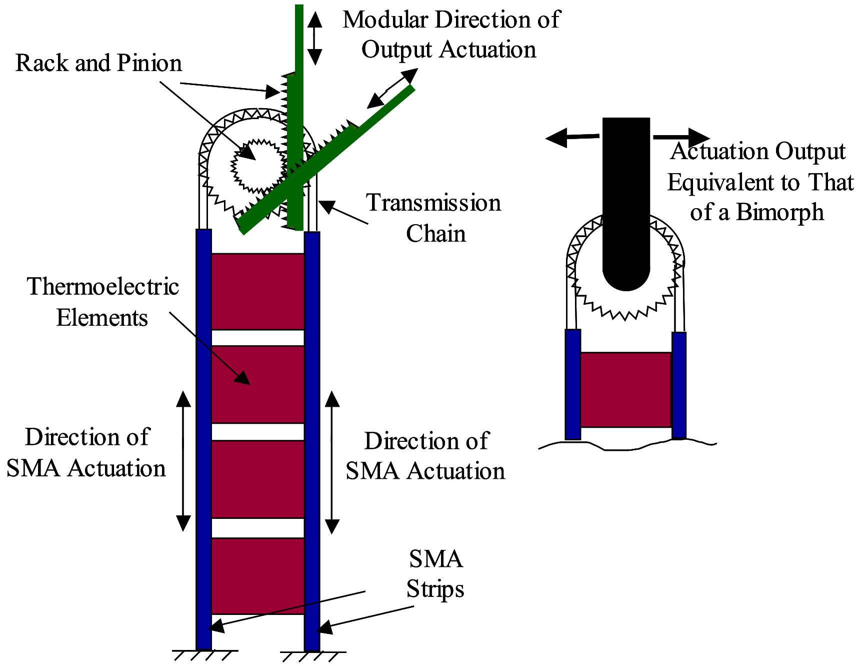
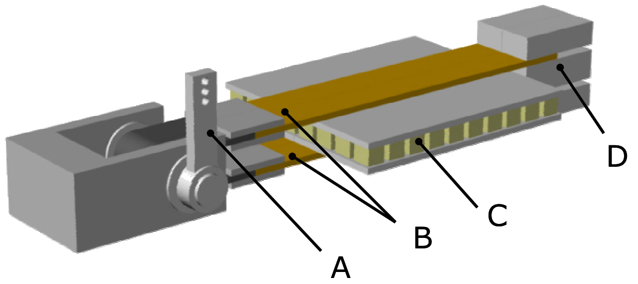


Figure 9. TEC-SMA Actuation Modes.



A: Actuator Arm
B: SMA Strips
C: Thermoelectric Element
D: SMA Mount

Figure 10. TEC-SMA Phase I Conceptual Model.

Phase I

Phase I of the project involves

- Design and construction of Phase I TEC-SMA:
  SMA strips (Nitinol).
  Thermoelectric element based on commercially available Peltier modules.
- Instrumentation:
  Stroke measured with LVDT (Res. 0.01 mm).
  Shaft rotation measured with optical encoder (Res. 0.09º).
  Load cell for output force measurements.
  Thermocouples for SMA temperature measurements.
  Supply voltage and current to determine thermoelectric element power consumption.
  Continuous measurements allow for closed loop actuation control.
- Optimize TEC-SMA bandwidth and stroke length based on both full and partial SMA transformation cycles.
- Parametric study of force, stroke and frequency
- Determination of Force vs. Displacement for actuator system at a range of actuation frequencies.
- Determination of TEC-SMA output power density and output energy density.

Phase II

Phase II of the project incorporates

- Analysis of Various SMA-Thermoelectric Interface Materials
    - Shear stress at thermoelectric / SMA interface.
    - Heat transfer characteristics.
- Actuator Performance Modeling
    - Constitutive model.
    - FEM analysis with ABAQUS and in-house codes.
- Prototype Fabrication
    - SMA strips, thermoelectric elements, interface material, and electrical circuitry.

3.2.2. Preliminary results

Figure 11 shows a schematic of a simple experimental setup involving an SMA strip as an actuator and two Peltier devices. The SMA strip is free to move on the cold surface of Peltier device using silicon based thermal paste to ensure thermal connection. NiTi SMA strip has cross sectional dimensions of 0.1 x 0.015 inches (2.54 x 0.384 mm), having a length of 1.702 inches (43.3 mm). The SMA strip is electrically heated using 30-60A current. Results of a preliminary test case are presented in Figures 12, 13 and 14. The results are for a time period of 0.5 Hz, with SMA actuation of 0.1 seconds with a constant SMA current-on to current-off ratio ($\tau = t_{ON}/t_{OFF}$, $\tau = 0.05$).

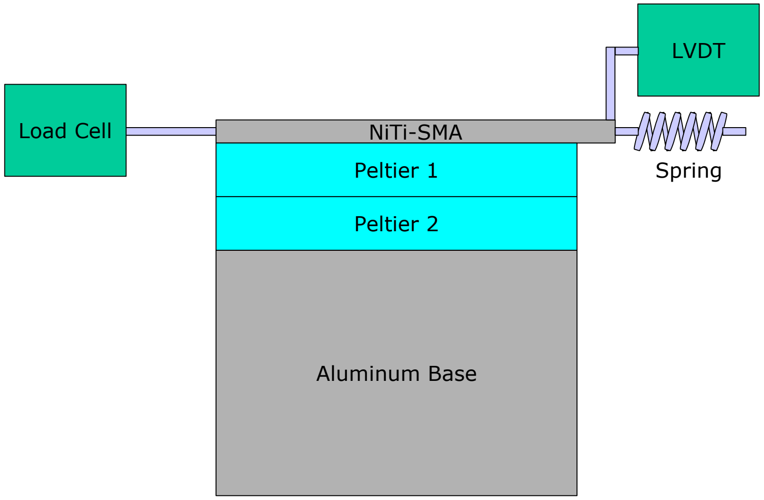


Figure 11. TEC-SMA experimental setup.

Figure 12 shows the variation of SMA actuator temperature with time. Figure 13 and 14 show the corresponding stress and strain response for the temperature profile shown in Figure 12.

Current work on the development of both the FPC and the TEC SMA actuator involves tasks outlined in phase I and II as mentioned above, and is part of on going research.

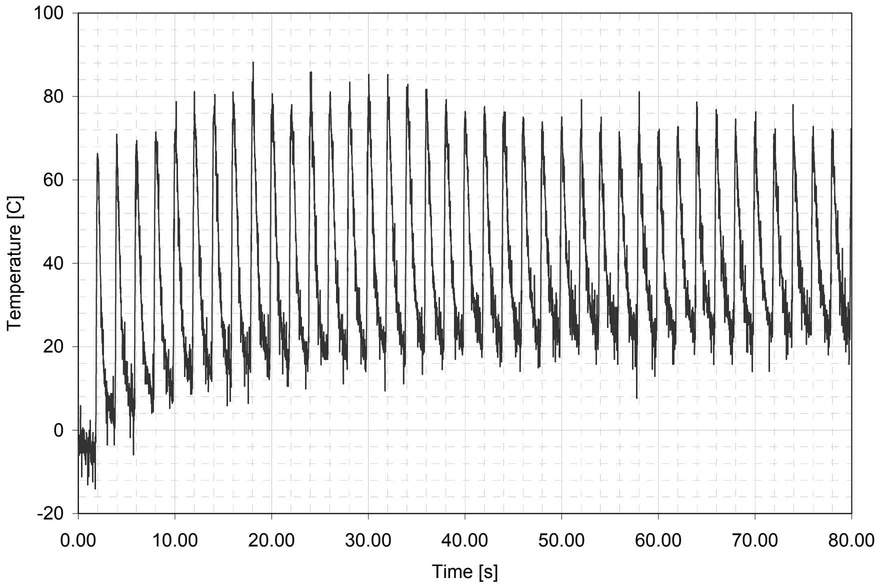


Figure 12. SMA Temperature.

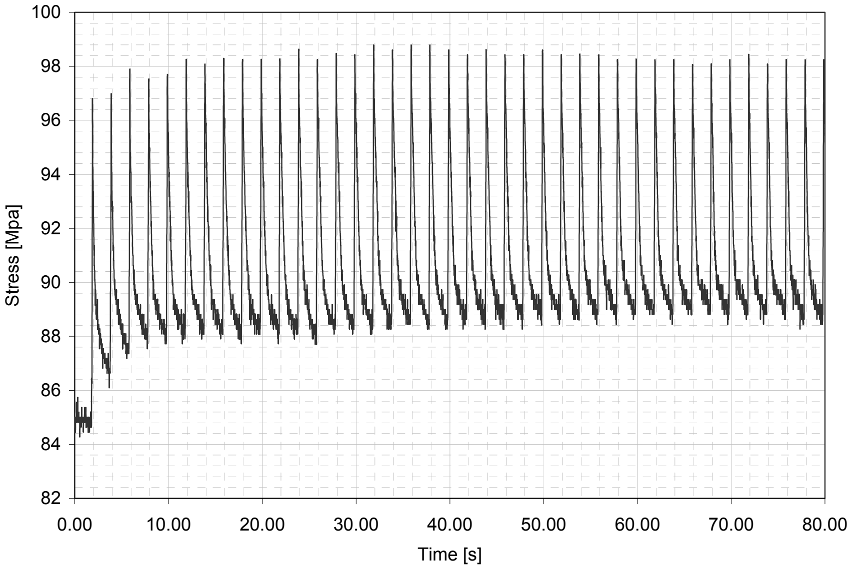


Figure 13. SMA stress.

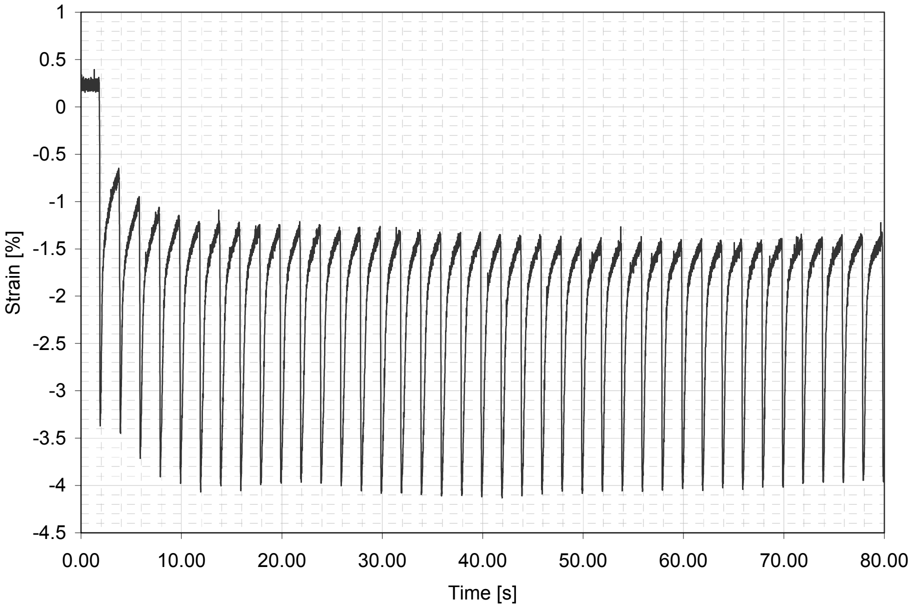


Figure 14. SMA strain.