The feasibility design and modeling for thermo-mechanical ocean energy harvester using shape memory alloys

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Abstract. In this paper a feasibility design of thermal energy harvester is proposed base on martensitic phase transformations in shape memory alloys (SMAs). Energy conversion from the thermal form to mechanical form via the martensite phase transformation in SMAs spring is modeled and analyzed. The phase transformation is induced thermally by the sea water temperature difference. In the proposed design, a macroscopic differential model of the two-way shape memory effects in one-dimensional SMA structure is employed to estimate the restoring force of the SMA spring. Power output is measured and found reasonable enough to be used. Thus the feasibility of the proposed design for ocean thermal energy harvesting is validated.

1. Introduction
From the viewpoint of non-renewability of fossil fuel coupled with the need to reduce CO₂ emissions that lead to global warming and the higher risk of nuclear power generation, efficient utilization of renewable safer and unused energy is highly desirable. Ocean Thermal Energy (OTE) is the second largest energy (10000 TWH/a) stored in the ocean, which is also very stable since the temperature change of ocean water is tiny and very slow. OTE is expected to be capable of providing mass and stable electric energy for some districts, and it could potentially be utilized as a source of virtually inexhaustible renewable energy [1].

The investigation on Ocean Thermal Energy Conversion (OTEC) has been a long history effort. Most of the researches and development have been based on the thermal dynamical Rankine cycle of low boiling medium. Various demonstrative OTEC equipment have been constructed, and testing operations have also been conducted in many different locations all around the world. So far, there is still no commercially sustainable OTEC equipment in the renewable energy market. The major difficulties of the OTEC technology based on Rankine cycle are all caused by the fact that the OTE is a poor quality one since the temperature difference between the warmer sea water on the surface of the ocean and the cold water in deep sea is rather small. The largest available temperature difference for the OTEC is about 25 degree, provided that the cold water could be lifted up from 5000 meters below the sea surface.

The low efficiency and unsustainability of the OTEC equipment based on Rankine cycle with a small sea water temperature difference can be easily explained by the following facts. Firstly, the heat exchange process and devices is very restrictive in order to extract out thermal energy from sea waters with a small temperature difference. Secondly, a massive amount of cooler sea water need to be transferred to the heat exchanger from the deep sea bottom, meanwhile the cooler sea water need to be...
thermally insulated. This obviously is energy demanding and technologically challenging. Lastly, sea water transportation and heat exchanging are conducted steadily and the equipment is stationary in sea water, therefore it is always a very difficult to clean the marine parasite on the equipment surface, since the marine parasite will grow quickly and deteriorate the heat exchange and transportation. The difficulties make the energy conversion so expensive and so low efficiency that it is normally unsustainable because the produced energy can hardly match the energy input into the system for operation.

Due to its unique property of automatic energy conversion via thermally induced martensite phase transformation, the SMAs have been considered, since its discovery, for usages in heat engine in many different ways for energy harvesting purpose. Among the existing designs, much effort has been devoted to their driving mechanism. SMAs engines were reported driven by crank, pulley, field, swash plate, reciprocating, sequential, etc. [2]. For energy harvesting from ocean thermal energy, the temperature difference is small and the warm area is far away from the cold area. Existing designs for SMA heat engine are not applicable.

In the current paper, an innovative design of hybrid energy harvester based on SMA heat engine is proposed to harvest ocean thermal energy. The proposed design consists of two energy converters. The major one is a SMA heat engine made out SMA spring chains, which is able to produce electricity by converting ocean thermal energy to mechanical work. The second one is a solar energy converter, which is responsible for collecting solar energy to help heat the surface sea water up so that the temperature is high enough to induce martensite phase transformation in SMAs springs. The detailed description and analysis of the proposed design is presented in the current paper.

2. Descriptions of the SMA spring
In the proposed heat engine, a SMA spring is trained by the procedure of heat treatment to have the shape memory effect. The SMA spring was heated up to 500 degrees Celsius, annealed for 30 minutes and then cooled down naturally. The critical temperature were set to be 35 degrees Celsius, and when the SMA spring is put into the environment with temperature over 35 degrees Celsius, there would be a sudden phase transition from austenite to austenite (or reverse martensite phase transition), and the spring would return to its original shape at higher temperature. This unique property of the apparent plastic deformation and subsequent full recovery is referred as the shape memory effects (SMEs) [3].

3. Principle operation of the SMA Spring heat engine
Rotation angles ($\theta_1$) and ($\theta_2$), are in contact with the spring through wrap angles (\(\varphi_1\)) and (\(\varphi_2\)). As this device is designed for generating electricity, an opposing moment (\(M_{ext}\)) is applied to output pulley 1, standing for an external load from an electric generator. Between points A and B, the SMA spring is under constant tension (F); Immersed in the heating chamber, the spring contracts and generates a higher tension (\(F+ \Delta F\)), simulating the sea surface with higher temperature. The timing pulleys have unequal radius (\(b_1\)) and (\(b_2\)). The timing belt is also under tension (\(F_t\)) on the top side, and some higher tension (\(F_t+ \Delta F_t\)) on the bottom side.

4. Kinetic and equilibrium analysis
According to the moment analysis, the equilibrium equations of moments around pulley 1 and 2 are obtained as follow, respectively:

\[
\begin{align*}
\alpha_1 \Delta F &= M_{ext} + b_1 \Delta F_t, \\
\alpha_2 \Delta F &= b_2 \Delta F_t.
\end{align*}
\]

(1)

Using the equilibrium equations above to eliminate (\(\Delta F_t\)), a single equation can obtained coupling \(M\) to the difference in tension (\(\Delta F\)) and dimensionless belt pulley ratio (\(b=b_1/b_2\)), where (\(0<b<1\)).

\[
M = \Delta F (a_1 - a_2 \frac{b_1}{b_2}).
\]

(2)

If \(a_1 = a_2 = a\)
Then, $M_{\text{ext}} = \Delta F \left( a \right) \left( 1-b_1/b_2 \right)$.

| No | Parameter                        | Values[unit] |
|----|----------------------------------|--------------|
| 1  | Original length of spring        | 700mm        |
| 2  | Tensile length                   | 1870mm       |
| 3  | Stretch ratio                    | 2            |
| 4  | F                                | 37.4N        |
| 5  | $\Delta F$                       | 36 N         |
| 6  | A                                | 75mm         |
| 7  | $b_1$                            | 60mm         |
| 8  | $b_2$                            | 10mm         |

According to the table 1 above, the additional moment $M$ can be obtained by Eq. (2), and $M = 0.48$ NM, which can make a small generator work to replace cell battery in some special devices when replacement of battery is difficult.

Figure 1 below is the schematic diagram of the proposed SMA heat engine system.

![Figure 1. The schematic diagram of SMA spring ocean energy harvester.](image)

5. SMA helical spring model development

For the purpose of establishing an engineering easy-to-use model, a well-understood mathematical model is given based on the modified Ginzburg-Landau-Devonshire theory:

$$\rho \ddot{u} = \frac{\partial}{\partial \sigma} \left( k_1 (T - T_c) \varepsilon + k_2 \varepsilon^3 + k_3 \varepsilon^5 \right) + \frac{\partial}{\partial t} \frac{\partial^2 \varepsilon}{\partial x^2} - k_g \frac{\partial^4 u}{\partial x^4}$$

Recast form:

$$\rho \ddot{u} = \frac{\partial \sigma}{\partial \sigma} + \frac{\partial}{\partial t} \frac{\partial^2 \varepsilon}{\partial x^2} - k_g \frac{\partial^4 u}{\partial x^4}$$

$$\sigma = k_1 (T - T_c) \varepsilon + k_2 \varepsilon^3 + k_3 \varepsilon^5 .$$

Where $k_1, k_2, k_g$ and $k_3$ are all constants; $\sigma$ is stress, $\varepsilon$ is strain, $t$ is time; $u$ and $v$ are initial and final velocity, $T$ is temperature; $c_v$ is time constant; $\rho$ is density of the material.
The equations (3) above are the mechanical field equations of the SMA rod [4]. L. Wang further modelled the above equation based on the design of the conventional spring and arrives at the following equation [5]:

$$\frac{d^2 x}{dt^2} + \nu \frac{dx}{dt} = a_1 (\theta - \theta_c) x + a_2 x^3 + a_3 x^5 + f(t) \quad (4)$$

Where $f(t)$ represents the external input to the system.

And finally:

$$F = a_1 (\theta - \theta_c) x + a_2 x^3 + a_3 x^5 \quad (5)$$

Where $a_1$, $a_2$, and $a_3$ are all constants, $F$ is the applied force, $x$ is strain or extension. When the parameters are set appropriately. The $F$-$x$ relation given in Eq. (5) is sketched in figure 2.

![Figure 2. Constitutive curve and predicted jump phenomenon.](image)

It can be seen that in figure 2, the constitutive curve is non-monotonic, leading bifurcation to the differential Eq. (4). The dashed lines in the plot represent the predicted jump. Thus the whole dynamic process can justify the hysteresis phenomenon of SMA spring [6].

6. Calculation
To calculate the values of $a_1$, $a_2$, and $a_3$

Assuming the following, length of SMA spring $L = 40$mm; Number of effective turn ($N$) = 6; spring radius, $R = 8$mm, SMA wire radius, $r = 0.75$mm; Taking $\tau = -2$

Several different numerical experiments have been carried out to demonstrate the strain-temperature relation in the SMA rod induced by the phase transformations. All experiments reported in the section have been performed on Au23Cu30Zn47 rod. Most of the physical parameters for this special material can be found in the literature [3-5], which are listed as follows for the sake of convenience:

7. Result
At ocean surface temperature $\theta_s = 290$K and ocean temperature at 100 meter below the surface $\theta_c = 265$K, the graph below shows the SMA spring behaviour based on the theory after inputting the calculated the values of constant.

8. The Power output of the SMA ocean harvester
For pulley, with the rotational angular speed is $\omega$ and the power output ($P$) is as follows:

$$P = M_{ext} \omega = \frac{2\pi M_{ext} N}{60} \quad (6)$$

Where $P$ is the output power, $M_{ext}$ is the imposed torque, and $\omega$ is the shaft angular velocity $N$ is the time it takes to make one revolution [7].
Since the SMA spring is the prime mover in the system, the power produces by this spring is equal to the above (6), and is calculated as below:

Mathematically power (p) is defined by the following equation:

\[ P = F \times v \]  \hspace{1cm} \text{(7)}

Where F= force; \( v \) is the linear velocity of pulley 2.

From the graph above we can assume that the maximum restoring force attained is 500N. Hence using the velocity of 0.05m/s, the power output of the machine can be calculated using (17) as follows:

\[ P = 500 \times 0.05 = 25 \text{watt} \]  \hspace{1cm} \text{(8)}

9. Discussion

Based on the graph above (figure 3), it can be seen that the SMA spring generate a hysteresis loop. And this is an indication that energy is stored after extension. The can be used to fuel heat engine. Also using the maximum load, the power of the engine is calculated as 25watt. This is reasonable enough to charge an electric battery.

![The graph of force versus strain](image)

**Figure 3.** The graph of force versus strain.

10. Conclusions

In this paper, a heat engine based on the shape memory effects (SMEs) is designed and a macroscopic differential model is constructed for the modelling of two-way shape memory effects in one-dimensional shape memory alloy (SMA) structures, which was modelled based on of the Ginzburg–Landau theory. According to the analysis above, this design is feasible.

Once the accurate power estimates for a given thermal gradient and engine geometry is provided, the model can not only provide guidance on which waste heat source offers the best chance of success, but it also can help optimize the engine geometry once a heat source has been chosen.

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