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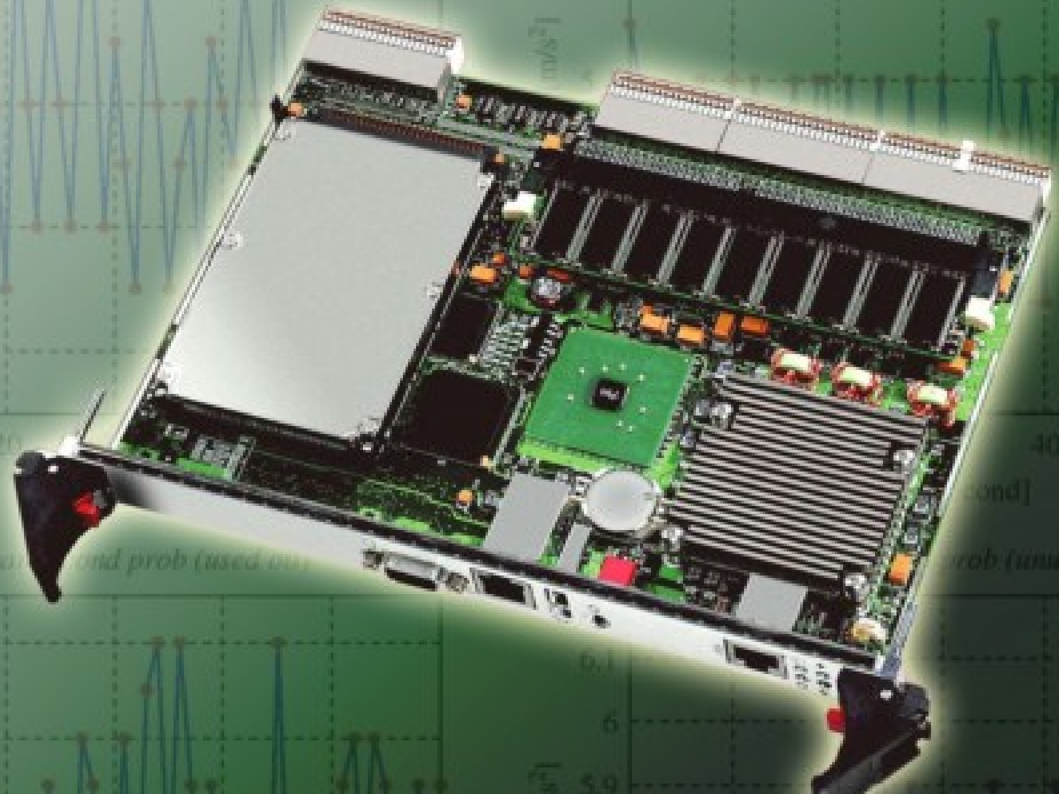

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Research of a Novel Attitude Regulating System of Autonomous Underwater Glider

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Abstract: The attitude regulating system plays a most important role in the autonomous underwater glider. A new attitude regulating system which is based on shape memory alloy is developed in this paper. Due to the characteristic property of the shape memory alloy, it is used as the driving material to achieve the goal of fast response. By analyzing the performance of the shape memory alloy wire, the dynamic model of attitude regulation system is established. An experiment is executed to verify that the new designed system presents is suitable to underwater glider. *Copyright © 2012 IFSA.*

Keywords: Attitude regulating system, Dynamic model, Fast response.

1. Introduction

Autonomous underwater gliders, represent a rapidly-maturing technology with a large cost-saving potential over currently-available ocean sampling techniques, especially for sustained, month at a time, real-time oceanographic measurements [1], as sketched in the Fig. 1(a).The motivation for developing autonomous underwater gliders is essentially economy [2]. Continuous weight changes as well as an attitude change result in a series of up/down glide cycles. The attitude regulating system plays a most important role in the autonomous underwater glider. Traditional attitude regulating system is sketched in the Fig. 1(b), but it needs other structure to help self-lock. Therefore, developing an adaptive gravity regulating system with fast response is the key to a successful autonomous underwater glider.

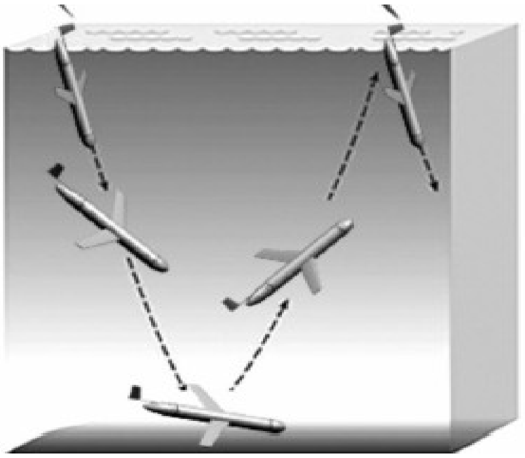


Fig. 1 (a). Autonomous underwater glider.

Fig. 1 (b). Traditional attitude regulating system.

It is known that a phase transformation in the shape memory alloys (SMA) is the major cause of the dramatic change of their physical properties under appropriate thermo-mechanical loadings. Many instructive investigations have been carried out towards a better understanding of the microstructure and phase transformation in ferroelastic materials [3-6]. With the unique mechanical characteristics and shape memory effect (SME), it has been used widely as force and displacement actuators in many fields, because it has the ability to return to some previously defined shape/size when subjected to appropriate thermal [7]. When the environmental temperature is lower than certain temperature, the SMA exhibits shape memory effect, and the environmental temperature higher than certain temperature, it exhibits the superelastic and hysteretic effect. The large recovery stress of 1GPa and large recoverable strain (6-8 %) capability of SMAs make them superior over other smart materials. In recent years, there has been surge in underwater glider research with many based on SMA actuation [8, 9] and other smart material actuators [10].

In the following section, a new kind of attitude regulating system of autonomous underwater glider was designed taking advantage of the superelasticity of SMA in order to overcome the limitations of the existed system. By use of the existed SMA dynamic model, a dynamic model of the proposed system is formed for the better understanding of the attitude regulating system.

2. SMA Attitude Regulating System

Fig. 2 is the structure of the attitude regulating system. The structure of using SMA wire to regulating displacement of the slide block is presented.

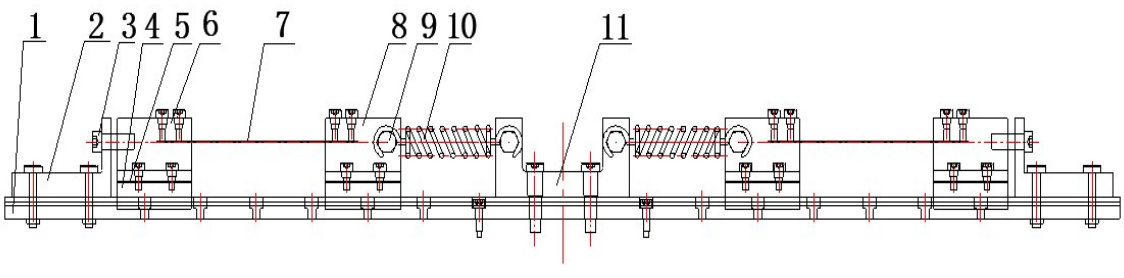


Fig. 2. Structure of the attitude regulating system.
1 - Linear guide rail; 2-L-liked block; 3-Preload screw; 4-Sliding block, 5-Insulated board, 6-Left T-liked block; 7-SMA wire; 8-Right T-liked block; 9-Fixed screw; 10-Spring; 11-U-liked block.

The system is completely symmetry from the center line. So here I describe the left side of the center line, which is the same as the other side. The system includes a linear guide rail. There are four sliding blocks on the linear guide rail and they can slide on the rail smoothly. Two T-liked blocks are placed on the sliding block and L-liked block is connected with left T-liked block through the preload screw. The SMA wire is fixed between the left T-liked block and right T-liked block through the screw. U-liked block is placed on the center of the rail. The spring is fixed between the right T-liked block and the U-liked block.

3. Working Principle of the Attitude Regulation System

The preload screw is screwed to make the SMA wire whose strain is about 0.08 stretch to its best. When the autonomous underwater glider is put into the water, the SMA wire is heated by electrifying. With the increasing of the SMA wire temperature, SMA phase converts from martensite to austenite. The SMA wire wants to restore to its original shape, which therefore pulling the sliding block to the left. The center gravity of the glider moves to the left of the center line. The glider's attitude moves to the left. When the glider gets to the lowest point, the system automatically cut off the current of the left wire to cool it and meanwhile the right wire is heated by electrifying. At the same time, the left SMA wire phase converts from austenite to martensite and the right SMA wire phase converts from martensite to austenite, which makes the left sliding block move back to the original position and the right sliding block move to right. Then, the center gravity of the glider moves to the right of the center line and the glider's attitude moves to the right. Depending on the pulse current, the glider can achieve attitude regulating in the water.

4. System Modeling

The system is completely symmetry from the center line. The scheme of the system is shown in Fig. 3. There is a mass block connected to a SMA wire. The SMA wire has an initial length L with an extending ΔL. The purpose of current investigation is to show the response effect of the attitude regulating system.

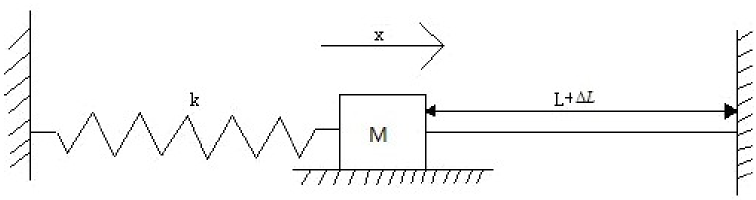


Fig. 3. Simplified physical model of the attitude regulating system.

Here for the mass block, the model can be easily formulated using the momentum conservation law as:

$$M\ddot{x}_M + \mu\dot{x}_M + kx_M = f \, , \tag{1}$$

where x_M is the position of the block; μ is the viscosity coefficient; k is the spring stiffness; M is the mass of the block, and f is the force on the mass block which is caused by the SMA wire discussed below. It can infer from the Fig. 3 that $x_M \in \Delta L$.

According to the thermodynamic principle and electrical resistance principle, we can get:

$$mc\frac{dT}{dt} = Ri^2(t) - hS(T(t) - T_0), \tag{2}$$

where m is the mass of the SMA wire; c is the specific heat of wire; R is the electrical resistance of the SMA wire; $S = \pi D^2 / 4$ is the cross-sectional area of the SMA wire; h is the heat convection coefficient.

Brison's model is now the most widely used SMA model .It is based on the Tanaka's model and Liang-Rogers's model. Brison's model phase transformation equation:

Austeniteto stress induced martensite:

If $T > M_S$ and $\left[\sigma_S^{cr} + C_M(T - M_S)\right] < \sigma < \left[\sigma_F^{cr} + C_M(T - M_S)\right]$

$$\xi_S = \frac{1-\xi_{S0}}{2}\cos\left[\frac{\pi}{\sigma_S^{cr} - \sigma_F^{cr}}\left(\sigma - \sigma_F^{cr} - C_M(T - M_S)\right)\right] + \frac{1+\xi_{S0}}{2} \tag{3}$$

$$\xi_T = \xi_{T0} - \frac{\xi_{T0}}{1-\xi_{S0}}(\xi_S - \xi_{S0}), \tag{4}$$

where σ_S^{cr} and σ_F^{cr} are the critical stresses at the start and finish of the conversion of the martensitic variants; C_M is the material properties that describe the relationship of temperature; M_S and M_F are the martensite phase start and final temperature respectively.

Compound twin martensite to stress induced martensite, $T < M_S$ and $\sigma_S^{cr} < \sigma < \sigma_F^{cr}$:

$$\xi_S = \frac{1-\xi_{S0}}{2}\cos\left[\frac{\pi}{\sigma_S^{cr} - \sigma_F^{cr}}\left(\sigma - \sigma_F^{cr}\right)\right] + \frac{1+\xi_{S0}}{2} \tag{5}$$

$$\xi_T = \xi_{T0} - \frac{\xi_{T0}}{1-\xi_{S0}}(\xi_S - \xi_{S0}) + \Delta T_\varepsilon \tag{6}$$

where

$$\Delta T_\varepsilon = \frac{1-\xi_{T0}}{2}\left[\cos\left(a_M(T - M_F)\right) + 1\right] \text{ at } M_F < T < M_S \;\&\; T < T_0.$$

When Compound twin martensite or stress induced martensite transform into austenite, its volume fraction changes as:

If $T > A_S$ and $C_A(T - A_F) < \sigma < C_A(T - A_S)$:

$$\xi = \frac{\xi_0}{2}\cos\left[a_A\left(T - A_S - \frac{\sigma}{C_A}\right) + 1\right] \tag{7}$$

$$\xi_S = \xi_{S0} - \frac{\xi_{S0}}{\xi_0}\left(\xi_0 - \xi\right) \tag{8}$$

$$\xi_T = \xi_{T0} - \frac{\xi_{T0}}{\xi_0}\left(\xi_0 - \xi\right) \tag{9}$$

where T is the SMA wire temperature; A_S and A_F are the austenite phase start and final temperatures; $a_A = \pi/\left(A_F - A_S\right)$ and C_A are curve fitting parameters.

By substituting $\xi = \xi_S + \xi_T$ into Liang's one dimension model, the equation can be obtained as follows:

$$d\sigma = \frac{\partial\sigma}{\partial\varepsilon}d\varepsilon + \frac{\partial\sigma}{\partial\xi_S}d\xi_S + \frac{\partial\sigma}{\partial\xi_T}d\xi_T + \frac{\partial\sigma}{\partial T}dT \tag{10}$$

It can also be described as:

$$d\sigma = Ed\varepsilon + \Omega_S d\xi_S + \Omega_T d\xi_T + \Theta dT \tag{11}$$

Set material parameters $E, \Omega_S, \Omega_T, \Theta$ as constant and the initial condition as $\sigma_0, \varepsilon_0, \xi_{S0}, \xi_{T0}, T_0$. Following equation can be obtained by integrating Eq. (11):

$$\sigma - \sigma_0 = E\left(\varepsilon - \varepsilon_0\right) + \Omega_S\left(\xi_S - \xi_{S0}\right) + \Omega_T\left(\xi_T - \xi_{T0}\right) + \Theta\left(T - T_0\right), \tag{12}$$

where E is the Young modulus; Ω is the phase transformation contribution factor; Θ is the thermal expansion factor; ξ_T is the fraction of the material that is purely temperature-induced martensite with multiple variants.

At the beginning of the phase transformation, the martensite volume fraction is 100 %, so $\xi_{S0} = 0$ and $\xi_{T0} = 0$ .Set $\sigma_0 = \varepsilon_0 = 0$, $\sigma = 0$, $\varepsilon = \varepsilon_L$, $\xi_S = 1$, $\xi_T = 0$ and $T = T_0\left(M_S < T < A_S\right)$, the following relation can be obtained:

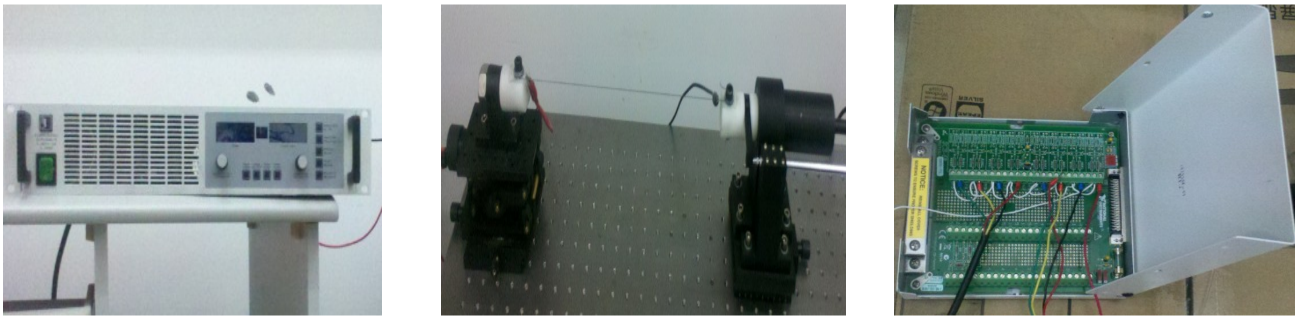
$$\Omega_S = -\varepsilon_L E\ , \tag{13}$$

where ε_L is the largest restoring strain. Then Eq. (12) can be simplified as:

$$\sigma - \sigma_0 = E\left(\varepsilon - \varepsilon_0\right) - \varepsilon_L E\left(\xi_S - \xi_{S0}\right) + \Theta\left(T - T_0\right) \tag{14}$$

5. Experiment and Model Simulation

An experiment has been carried out to demonstrate the high response of the new attitude regulating system of the underwater glider. The effective length of SMA wire in the new attitude regulating system is only 40 mm. The experiment which is reported in this section has been performed on a TiNi SMA wire with length of 350 mm for convenience. At first we fixed the SMA wire on the device like Fig. 4. Then we extend the wire to another 7 mm (2 % of the original length) and set the objective force 100 N, which means that the wire is always suffered from a 100 extruding force in the process of contracting. The current from 1.0 A to 2.5 A is given to the wire through PS 8000 2U power supply. After the wire have completely contracted, the current is cut off in order to make the wire cool off in the air and extend to original displace under the 100N objective force. The experiment date can be obtained by NI M-series DAQ.



(a) (b) (c)

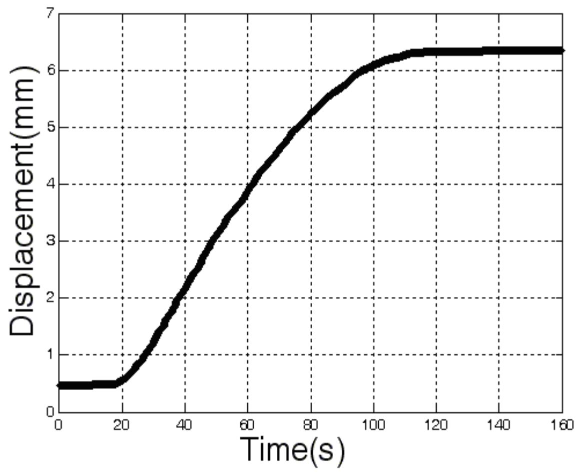
Fig. 4. The experiment equipment including: PS 8000 2U power supply (a); SMA fixing device (b), and NI M-series DAQ (c).

The experiment results are shown in Table 1 and the relationship between time and displacement is present in the Fig. 5.

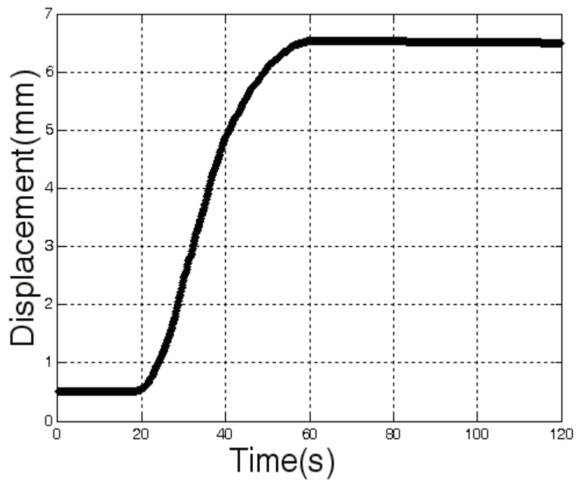
Table 1. Part of the experiment data under different current.

1 A		**1.5 A**		**2 A**		**2.5 A**	
Time, （s）	Displacement, （mm）	Time, （s）	Displacement, （mm）	Time, （s）	Displacement, （mm）	Time, （s）	Displacement, （mm）
20	0.4665	20	0.5309	40	0.5063	20	0.5468
26	0.9032	23	0.8653	42	0.8875	21	0.6412
32	1.4399	26	1.3712	44	1.8133	22	0.9244
38	2.0044	29	2.1059	46	3.0132	23	1.2522
44	2.5189	32	2.9486	48	4.6895	24	1.7817
50	3.1581	35	3.7847	50	4.9096	25	2.4365
56	3.5852	38	4.4976	52	5.4391	26	3.2594
62	4.0482	41	5.0078	54	5.7671	27	4.0517
68	4.4781	44	5.4314	56	5.9279	28	4.8589
74	4.8935	47	5.7992	58	6.0787	29	5.2117
80	5.2357	50	6.0877	60	6.1537	30	5.4893
86	5.5429	53	6.2616	62	6.2679	31	5.6703
92	5.7911	56	6.4418	64	6.3437	32	5.8144
98	6.0466	59	6.5142	66	6.3792	33	5.9468
104	6.1807	62	6.5352	68	6.4177	34	6.0141
110	6.2683	65	6.5354	70	6.4368	35	6.0421
116	6.3317	68	6.5355	72	7.44448	36	6.1170

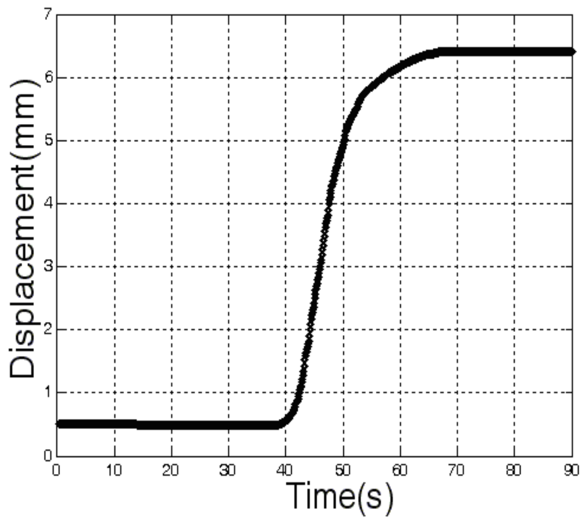
The data in Table 1 are taken into Matlab and the following curve Fig. 5 can be obtained.



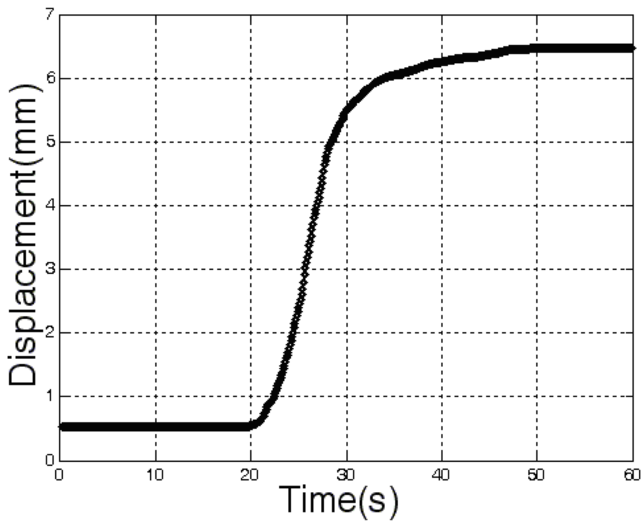
(a) I=1 A



(b) I=1.5 A



(c) I=2 A



(d) I=2.5 A

Fig. 5. Time-displacement curve under different current.

We can get from the Fig. 5 that the SMA wire contracts very quick under the effect of different current and restores to its original shape completely. With the increasing of the current, the SMA wire shows high contract speed and short response time with stronger response stress. However, the current shouldn't be too heavy, which will make the wire so hot that decrease the steady of response stress. In addition, it can be inferred from Fig. 5 that the experimental data shows an exponential distribution that is there is an exponential relationship between phase transformation and heating current.

We use the same load, heating current and SMA wire parameter during simulation and experiment, In order to have a comparability of quantification with feasibility of experiment between simulation of SMA wire driving and experiment result. All simulations reported here have been carried out for NiTi SMA wire with a length of 354 mm. its physical parameters are available as follows:

$$M_f = 26^\circ \mathrm{C}, M_s = 40^\circ \mathrm{C}, A_s = 65^\circ \mathrm{C}, A_f = 80^\circ \mathrm{C}, \mathrm{C}_M = 28MPa/^\circ \mathrm{C}$$

$$\mathrm{C}_A = 40MPa/^\circ \mathrm{C}, \Theta = 1.5MPa/^\circ \mathrm{C}, resistivity\,\rho = 8.0\times10^{-7}$$

$$density\,\rho = 6.5\times10^{3} kg\cdot m^{-3}, c = 460J/\left(m^{2}\cdot^{\circ}C\right), h = 70W/(m^{2}\cdot^{\circ}C)$$
$$D = 0.3048mm, E_A = 35917MPa, E_M = 16800MPa$$

Computer simulations of the SMA model were performed in MATLAB/Simulink by using Eq. (2) and Eq. (12) and then Fig. 6 can be obtained. It shows that the result of experiment and simulation are almost the same but only have little different at the beginning.

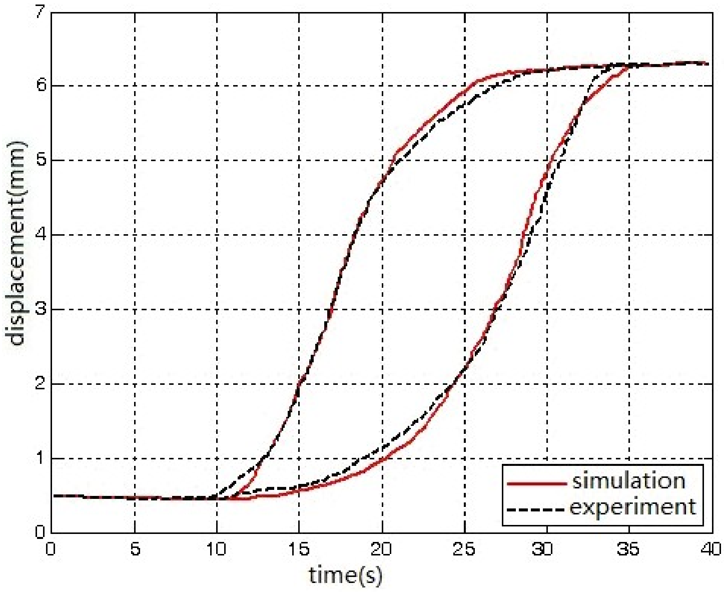


Fig. 6. Simulation and experiment comparison curve.

The experiment result of displacement-time curve shows that at the beginning of electrifying, SMA wire stays in martensite phase. The SMA wire has a prestretch suffering from the force sensor, so the Fig. 6 has a downturn process. With the increasing of the SMA wire temperature, it will change from martensite to austenite and the wire start to contract, so the curve shows the ascending process. The phase transformation is very fast which only needs little time. When SMA wire turns into austenite completely, it will stop contracting and the curve presents horizontal extending. According to the Fig. 6, there is little difference between simulation and experiment result, but it is basically the same in the process of deformation restoring. Therefore, SMA is the best material used to driving attitude regulating system which will make the underwater glider response fast with high efficient.

In the end, the current is given to TiNi SMA wire of the new attitude regulating system to test whether it can regulate attitude or not. First time when the current is given to the wire, the wire contracts to the original shape and pull the adaptive block to the one side, which, on the other hand, change the gravity center of system to one side. So the whole attitude regulating system tilts to one side, realizing the goal of regulating attitude of system. The attitude of the new system before and after electrifying can be seen in Fig. 7 (a) and Fig. 7 (b).

It can be inferred from Fig. 7 that the new designed attitude regulating system satisfies our requirements of regulating attitude quickly and precisely and the TiNi SMA wire is the most suitable material to driving the system.

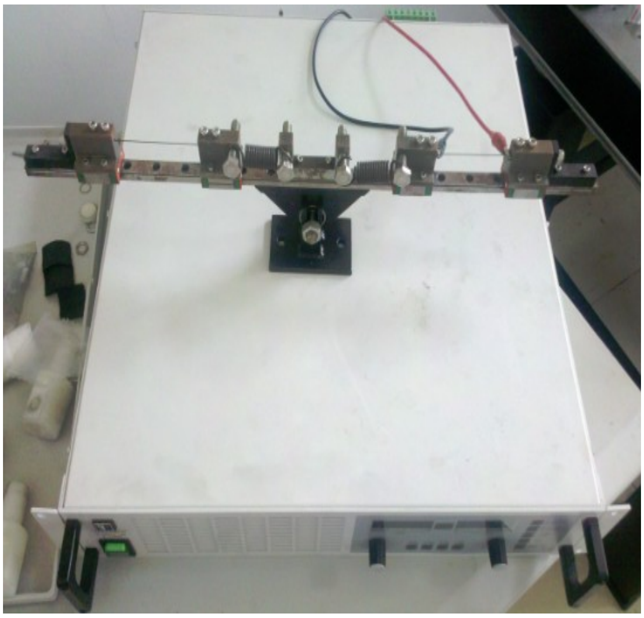


Fig. 7 (a). Before electrifying.

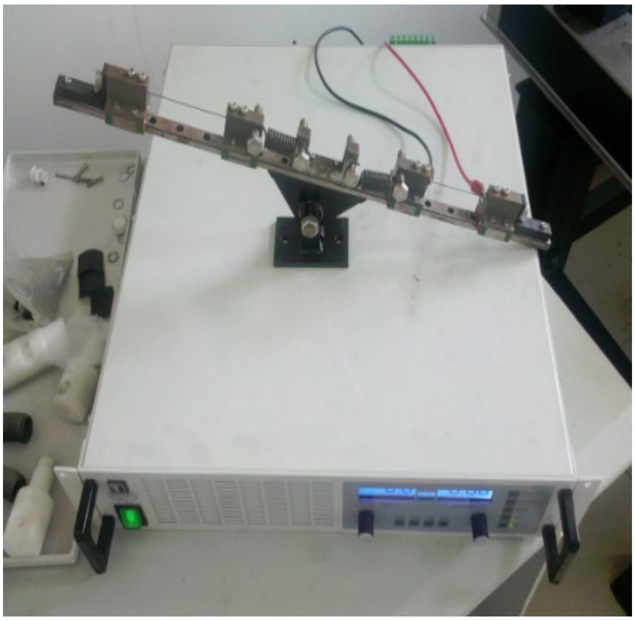


Fig. 7 (b). After electrifying.

6. Conclusion

A novel design of shape memory alloy based attitude regulating system is developed in this paper. The dynamic model of attitude regulation system is established based on the SMA constitutive model. An experiment is finished, which shows the new designed attitude regulation system satisfy the requirement of the underwater glider. In addition, SMA wire is the most suitable material to drive the attitude regulating system.

Acknowledgement

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Guide for Contributors

Aims and Scope

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