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Possibility of temperature control on the test point study of elastomer properties

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The system of control and maintenance of temperature in the tank used for fatigue tests of the elements is presented. The designed system enables reaching and maintaining a constant temperature in the range from 17 to 45°C with a slope of $\pm 0.5^\circ\text{C}$. The temperature control system was implemented using the Peltier cells and the Arduino Uno control system.

KEYWORDS: *temperature control, Peltier module, properties of elastomers, temperature control system*

Introduction

Formation of new materials is a very important factor affecting the shape and parameters of products. Typical materials are steel alloys, ceramics, elastomers and composite materials.

Elastomeric materials are macromolecular compounds having the ability to reversibly deform under the influence of external forces at room temperature. An important feature of them is the dependence of mechanical properties on temperature changes [2–4]. For this reason, it is necessary to study the operation of elastomer elements in various environmental conditions to determine their suitability. They are used, for example, in adaptive shock absorption systems [1].

The stand for testing elements made of elastomers described in the paper was created for the needs of a company dealing in the design and production of chassis systems, structural elements and mechanical components of propulsion systems. The purpose of the research was to develop a method for measuring and controlling the temperature in the tank used for fatigue testing of elements made of elastomers. Before designing the temperature control system, the requirements for the described system were determined.

Requirements for the temperature measurement system

Temperature control system should enable temperature selection from 17 to 45°C with an accuracy of 0.5°C. The task of the system is to obtain and maintain a specific temperature with an accuracy of $\pm 0.5^\circ\text{C}$ relative to its set value, in the test stand tank. This solution should be resistant to the influence of ambient temperature.

The system is to be programmatically capable of responding to temperature changes, regardless of the degree of thermal insulation provided by the container.

The test stand should include:

- tank with a capacity of approximately 1 m³ filled with air,
- Peltier cell placed in the tank wall,
- radiators attached on both sides of the cell, which will facilitate the flow of thermal energy, with two of them to be on the active side of the cell, inside the test tank, and the other two on the reactive side of the cell, outside the tank,
- 30 W fans attached to the radiators and ensuring continuous air flow.

Peltier module

The Peltier module is a semiconductor thermoelectric device that uses the reverse Seebeck effect for heat transfer. It has many applications [5, 6].

It should be noted that this element does not absorb or emit heat, but serves only as a heat pump, which transports heat energy in the direction depending on the polarization of the circuit. It consists of two ceramic plates placed in parallel, between which "n" and "p" semiconductors are placed alternately. Ceramic tiles are to ensure mechanical rigidity and perfect electrical insulation. Good thermal conductivity is an important feature.

Semiconductors used are made of bismuth telluride admixed with antimony and selenium. They are connected in series with copper plates. As it is known, the "p" type semiconductor lacks electrons to fully fill the upper energy level, and the "n" semiconductor has an excess of electrons (Fig. 1). There are two cases at the time of current flow:

- energy consumption from the environment when the electron enters a higher energy level,
- release of energy into the environment when the electron falls to a lower energy level.

In both cases, thermal energy is considered. Because semiconductors are connected in parallel in terms of heat, the Peltier module simultaneously emits and absorbs heat. It is referred to as so-called hot and cold side. It should be noted that the amount of heat transferred is not equal to the amount of heat absorbed (more heat is transferred).

Fig. 1. Diagram of the Peltier module

Temperature control system

The heart of the system, responsible for controlling the designed temperature measurement system, is the Arduino Uno multifunction device. Arduino is an open-source project created in 2005. It consists of sets based on microcontrollers for the construction of digital devices and interactive objects that can detect and control physical devices.

The Arduino Uno (Fig. 2) contains an ATmega328P microcontroller equipped with six analog inputs with a resolution of 10 bits and 14 digital inputs/outputs (using six of them you can generate a PWM signal). The whole is clocked with a 16 MHz quartz crystal.

Basic function of the system is to provide a specific temperature value in the tank, in which fatigue tests will take place. To do this, measure the temperature both inside and outside the tank. DS18B20 digital sensors were used to measure the temperature. They provide 9 to 12-bit temperature measurement. Their measuring range is from -55 to +125°C, and their accuracy depends on the measurement resolution used and ranges from 0.5°C

for 9 bits to 0.0625°C for 12 bits. As the resolution increases, the measurement time increases from 93.75 ms for 9 bits to 750 ms for 12 bits.

Fig. 2. Arduino Uno microcontroller board [7]

Four measuring sensors were used in the described system. One controlled the temperature in the tank, the other was used to measure the temperature outside the tank, while the other two were used to measure the active and reactive side of the Peltier module.

In addition, it was important to control the operation of Peltier modules. It was necessary not only to change the mode, in which they were to work (heating or cooling), but also to control the value of thermal energy that was thus supplied to the tank. To achieve this, PWM regulation should be used with the option of changing the direction of the current. This is ensured by the use of the LXR Brushless Motorshield half bridge. It can generate a PWM signal with a frequency up to 25 kHz.

The designed system is divided into a part responsible for power supply and temperature change in the tank (the so-called external system) and a logical part. Fig. 3 shows the external system.

**Fig. 3. Four Peltier modules placed between two radiators the main part of the external system:
1 -active radiator, 2 - passive radiator, 3 - Peltier module,
4 - fan ensuring flow through the active radiator, 5 -passive radiator**

The power supply fed four parallel Peltier modules and a logical part connected together. The modules are evenly and thermally distributed in parallel between two radiators. The whole was screwed together using four aluminum plates and mounting screws.

Power supply in the logical part was directly connected to the Arduino power supply system and the Motorshield half bridge. All elements of the logical part have been mounted on the board. The whole logical part was placed in the housing (Fig. 4).

Fig. 4. Logical part: a) internal structure, b) housing

The front of housing has holes for sensor connectors, programmer, output for powering Peltier modules and a socket from the power supply. On the same side of the housing, there are mounted inputs for the power supply and outputs that supply the appropriate PWM signal Peltier modules.

Before writing the control code, it was considered necessary to check the impact of PWM on the temperature in the tank. To this end, it was necessary to build a test stand that would more or less reflect the working conditions. A plastic container and PVC pipes were used for this.

The tests consisted of measuring the air temperature inside the test tank with the cooling system on and the PWM signal set. The measurements were carried out at the same possible initial temperature in the tank.

Fig. 5 shows the relationship between PWM signal fill and tank temperature. However, Fig. 6 shows the relationship between the digital value of the PWM signal and the temperature drop in the tank.

The temperature drop in the tank was calculated from the formula:

$$\Delta_{tN} = \frac{T_N - T_{N-1}}{t_N - t_{N-1}} [^{\circ}\text{C}/\text{min}] \quad (1)$$

where: T_N , T_{N-1} – temperature [$^{\circ}\text{C}$] in the tank during N -th and $N-1$ measurement, respectively, t_N , t_{N-1} time [min] during N -th and $N-1$ measurement, respectively.

Based on the results analysis, it can be seen that:

- temperature achieved in the tank decreases as the signal fill decreases,
- over time, the rate of temperature drop in the tank decreases (for constant signal strength).

The ambient temperature has a large impact on the temperature achieved (this effect increases for low power signals). For a signal of any power, given external conditions, there is a set achievable temperature value in the tank.

It is worth noting that the measuring stand was not an exact copy of the target tank. The target tank will be made of a different material (probably steel) and will be thermally insulated. The active heat sink will be located inside the tank.

Despite the differences, the results give an idea of the effect of the degree of signal filling on the temperature in the tank. Based on the measurements at the test stand, a limit on the temperature range achievable in the tank was introduced. The user will be able to choose a temperature from 17°C to 45°C . Reaching temperatures outside this range may not be possible (for the cooling process at high ambient temperature) and very time-consuming (over 20 min) (Figs. 5 and 6).

Fig. 5. Relationship between digital value of the PWM signal and temperature in the tank

Fig. 6. Relationship between digital value of the PWM signal and temperature drop in the tank

The basis for the operation of the temperature control algorithm is to adjust the value of the PWM signal controlling the Peltier modules in such a way that achieving the temperature is as fast as possible (according to the client, the maximum time to reach the set temperature cannot exceed 10 min), there were no overshoots, the system was resistant to changes in ambient temperature and consumed as little power as possible.

The control algorithm is divided into the following stages:

- reaching temperature,
- stabilization stage,
- special stage,
- temperature maintenance stage.

During each of these stages, the system measures the temperature: ambient, inside the tank, active side and reactive side of the Peltier cell.

Mode selection stage

After the user enters the desired temperature, the system decides whether to cool or heat the air in the tank. This is due to the difference between the desired temperature and the temperature inside the tank (if the value of this difference is 0, the system will switch to cooling mode and the control algorithm will implement the special stage directly).

Temperature reaching stage

The task of the system during the initial stage of achieving temperature is to determine the value of the parameter x from the formula:

$$X = \frac{t_w - t_z}{t_z} \quad (2)$$

where: t_w air temperature inside the tank, t_z set temperature in the tank.

If the value of the parameter x is greater than or equal to 0.1, the system with maximum power strives to reach the set temperature inside the tank, which is equivalent to setting the PWM fill level to 100%.

If the value of parameter x is between 0.1 and 0.05, the system will strive to reach the set temperature at a lower speed. As a result, the likelihood of overshoots has been minimized. In this case, the PWM signal fill level was experimentally set at 81% of the maximum power.

Stabilization stage

If the value of the parameter x falls below 0.05, which corresponds to a temperature range of $\pm 0.5^\circ\text{C}$, the control algorithm goes to the stabilization stage. The temperature control algorithm defines certain ranges (Fig. 7). The idea of maintaining a set temperature in the stabilization range is to power the cell properly depending on the area, in which it is located.

The software, by smoothly changing the degree of PWM filling, strives to stabilize its value at an optimal level. This means that the Peltier modules will be supplied with constant power, ensuring that the set temperature in

the tank is maintained under appropriate external conditions. Peltier modules operating in this way will have a longer life than modules, in which the supply current will be variable.

	+0.5°C	Out of range
Set temperature		Positive range allowed
		Negative range allowed
	-0.5°C	Out of range

Fig. 7. Temperature ranges used in the designed control algorithm

Fig. 8 shows an example of temperature changes inside the tank during cooling: 1 – the temperature reaches the permissible range; 2 – temperature reaches the set value; within the allowable range with a specified tolerance of $\pm 0.5^\circ\text{C}$, the PWM signal fill value is reduced; 3 – the temperature exceeds the allowable range due to the PWM supply signal being too full; the degree of PWM signal saturation is reduced; 4 – the temperature returns to a state within the permissible range; 5 – the temperature reaches the set value again; the PWM signal fill level is increased.

Fig. 8. Example of the temperature inside the tank during cooling

The algorithm also has protection against temperature stabilization out of range. It involves increasing or decreasing the PWM signal's fill level (from time to time) until the temperature returns to the acceptable range. The main tasks of the stabilization stage are:

- stabilization of the temperature value in the tank within the permissible range (within a tolerance field of $\pm 0.5^\circ\text{C}$),
- achieving small temperature oscillations inside the tank around the set temperature.

If one of these goals is met, the algorithm goes to the temperature maintenance stage and supplies the cells with constant power.

Special stage

The algorithm will go to this stage if it is equal to the temperature inside the tank when the user selects the set temperature. This stage is almost the same as the stabilization stage, but the PWM signal fill value is preset to 50% instead of 81%.

Temperature maintenance stage

This is the final part of the control procedure. It does not differ much from the stabilization stage except that:

- The algorithm responds to 'limits' and out of range stabilization, but changes in PWM signal fill values do not decrease. The value of changes was already reduced during the stabilization phase and one of the goals was met.

- The algorithm will respond to long-term changes in ambient temperature. During many hours of testing, the ambient temperature may change so much that it will be necessary to change the operating mode of the Peltier modules, e.g. at the time of starting the system, the ambient temperature (and hence the initial temperature in the tank) was higher than the set temperature. The control system was in "cooling" mode. After a few hours, the ambient temperature dropped below the set temperature in the tank. For this reason, the control system automatically goes into "heating" mode. The automatic change of operating mode has been introduced to the control system in order to enable the temperature measurement in the tank during long-term tests of materials made of elastomers.

Summary

All requirements regarding the form and functionality of the system have been met. The designed control algorithm works correctly. The desired temperature is reached in up to 10 min, regardless of external conditions, and is stabilized within the specified range.

During the tests, no overshoots greater than 2°C were observed. The control algorithm responded correctly to changes in ambient temperature, ranging from changing the value of the PWM signal fill up to changing the operating mode. Providing automatic change of operating mode depending on the ambient temperature, e.g. from "heating" to "cooling", allows for long-term (over 24-hour) fatigue tests of elastomeric materials.

There are many possibilities for development of the designed control system. In order to improve functionality and reduce overshoot of the set temperature, one should design a control system based on PID control and compare the efficiency and reliability of both solutions during both short-term and long-hour operation.

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