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Design and development of atomic flux controller for cesium Fountain clock at NPL, India

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In the present paper, the development of an electronic module for controlling the atomic flux from Cesium (Cs) Source (Cs ampoule) to the cooling chamber of Physics package of Cs fountain clock being developed at National Physical Laboratory (NPL) India, is described. Cs source is integrated with octagonal cooling chamber and the amount of Cs diffusing into the chamber is controlled by controlling the temperature of Cs ampoule. The atomic flux controller is basically a temperature controller which is designed for maintaining the temperature from 10°C to 80°C. It is based on lock-in amplifier and proportional-integral-differential (PID) controller techniques for precise control of temperature. We have used Thermoelectric Coolers (TECs) for cooling and heating the Cs ampoule.

Keywords: Thermoelectric coolers, Wheatstone bridge, Lock-in amplifier, Phase shift, Feedback control

1 Introduction

We have been developing India's first ever Cs fountain frequency standard[1] at the NPL. Cs source is the heart of the system and supplies Cs atoms to the octagonal cooling chamber where the atoms are subjected to three pairs of counter propagating laser beams and magnetic field gradient for cooling and trapping. In general, there are two types of sources used for loading the magneto-optical trap (MOT): a getter source and an ampoule[2,3].

The getter source is a commercially available dispenser of alkali atoms designed for industrial applications. It contains an alkali compound and a reducing agent enclosed in a stainless-steel boat. The compound is stable at room temperature and the boat can be handled easily without fear of contamination. When a few ampere of current is passed through the boat, its temperature rises to several hundred degrees celsius. At these high temperatures, the compound undergoes a reduction reaction and atoms are released. Another type of source is a small sealed glass ampoule containing about 1 g of alkali compound is installed in a thin-walled stainless steel or copper tube. One end of the metal tube is sealed, and the other end is welded or brazed onto a 1.33 inches wide Conflat-type flange which is attached to a valve connected to the main cell. After the system has been thoroughly pumped out and baked, the tube is squeezed in a locking pliers (vice grips) until the metal wall has compressed enough to break the glass and the atoms are released.

For experiments like atomic fountains where a constant and steady supply of atoms are required, a better method is to have atoms diffusing into the MOT chamber. As shown in Fig. 1, the vapour pressure of Cs increases with increasing temperature[4]. To get the atoms through the valve and into the cell, the tube and the valve are heated to 60-80°C. For the first time this is done, large atomic reservoir connected to the cooling chamber via a stainless steel valve. Therefore, in our set-up, we use a Cs ampoule as atomic source for loading the MOT. The ampoule can be heated or cooled in order to change the flux of atoms (when the chamber is empty) it takes between several hours and several days to see a significant amount of atoms in the cell.

Once the walls of chamber are coated with Cs, it is sometimes needed to even cool the Cs source below the room temperature because at room temperature, the vapour pressure of Cs is much more than the optimum pressure needed for trapping[3]. Too much vapour pressure inside the chamber will absorb lot of power from the trapping beams and will also make it difficult to observe the trapped atoms due to bright fluorescence from the untrapped background atoms. Thus, the flux of atoms is required to be controlled by controlling the temperature of the Cs source. In the present paper, the design and development of the

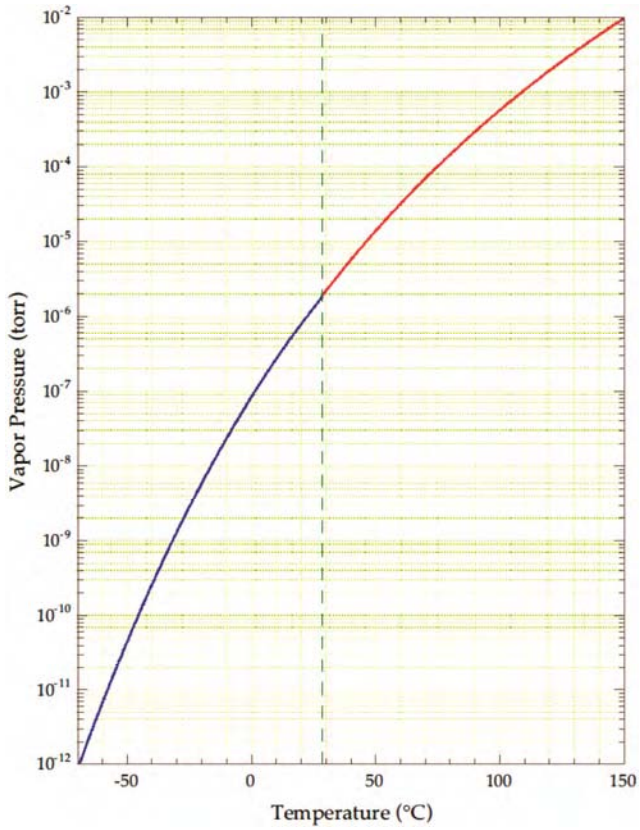

Fig. 1 — Vapour pressure of Cs as a function of temperature[4]

cooling assembly based on thermoelectric coolers (TECs) and a closed loop PID temperature controller circuit, have been reported. The temperature controller can maintain the temperature of Cs source from 10°C to 80°C with an accuracy of 0.1°C. While Cs fountain is in operation, the temperature of Cs is kept around 10°C.

2 Cs Source Flux Controller-Design Details

The block diagram of the system is shown in Fig. 2. This consists of Cs source cooling and heating assembly, closed loop PID temperature controller and temperature display circuits.

2.1 Cs Source Cooling and Heating Assembly

The Cs source is in the form of a small cylindrical ampoule of about 4 cm height and 1.2 cm diameter and contains about 1 g Cs. Two aluminium blocks of size 40 mm×40 mm×15 mm with semi-cylindrical slots of height 40 mm and radius 6.6 mm at the centre were fabricated to accommodate the Cs ampoule between them. The mechanical drawing of these blocks is shown in Fig. 3 and act as cooling or heating plates for the ampoule. We have used thermoelectric

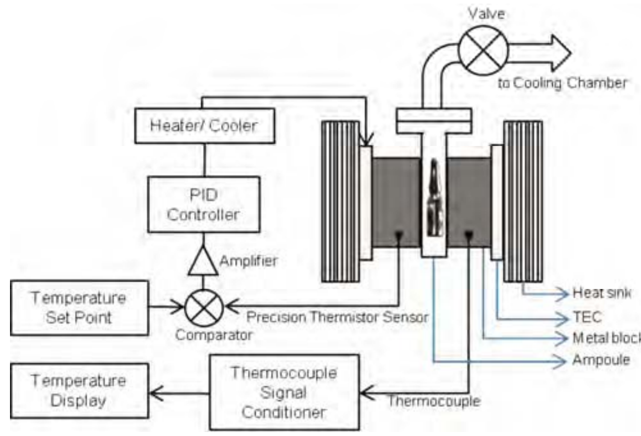

Fig. 2 — Block diagram of Cs source temperature controller unit

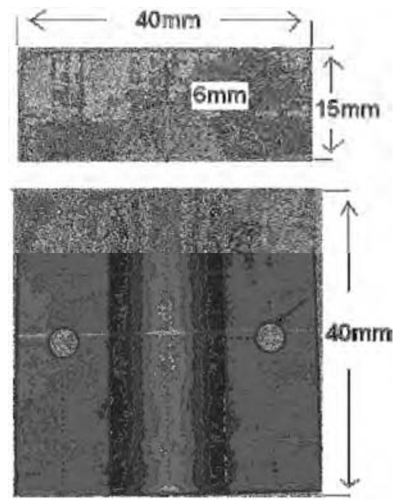

Fig. 3 — Mechanical drawing of Al cooling blocks

Table1 — Specifications of thermoelectric cooler (TEC) HT8-12-40

Hot Side Temp (°C)	25°C	50°C
Qmax(watts)	72.9	80.0
Delta Tmax °C	63.0	75.0
Imax Amp)	8.50	8.50
Vmax (Volts)	14.50	16.40
Module Resistance	1.58	1.78
Max Operating Temp.	200 °C	

coolers (TECs) HT8-12-40 (size-40 mm×40 mm-Fig-2) manufactured by Melcor (http://www.melcor.com) for cooling and heating these Al blocks. Table 1 presents the specifications of these devices. One pair of TECs is sandwiched between the plane sides of both Al blocks and heat sinks by using a good quality non-silicon thermal grease HTC-100 (thermal conductivity @ 36°C = 5.0W/m-k) manufactured by AOS (http://www.aosco.com).

The cut view of the assembly is shown in Fig. 4, the space between Al blocks and heat sink is filled with insulating material. Due to limited space available in the physics package for installation of the cooling module, we could not increase the size of heat sinks to reduce the temperature of the object to substantially low level with single stage cooling (one TEC on each side). Therefore, we have used a two stage cooling i.e. two devices on each side to reach the lowest possible temperature. The size of the module is 100 mm×110 mm×100 mm. For feedback control the temperature of the Cs ampoule is sensed by a thermister attached firmly with the Al block. Fig. 5 shows Cs source cooling module integrated with the octagonal chamber of Cs fountain.

2.2 Temperature Controller

Figure 6 shows schematic diagram of temperature controller. It has three main parts viz. lock-in amplifier, PID Controller and power amplifier for driving the load.

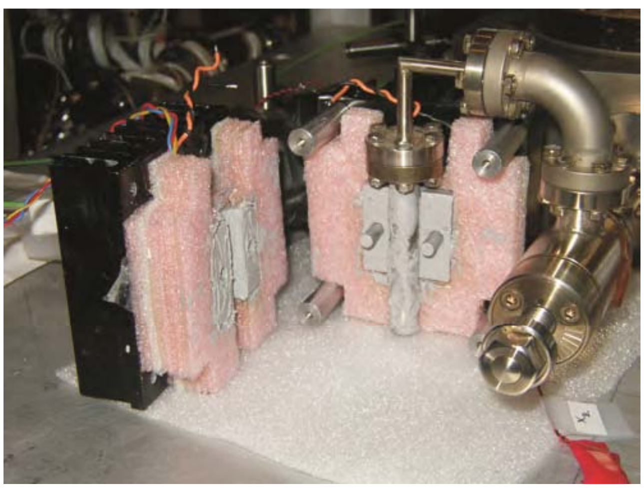

Fig.4 — Cut view assembly of Cs module

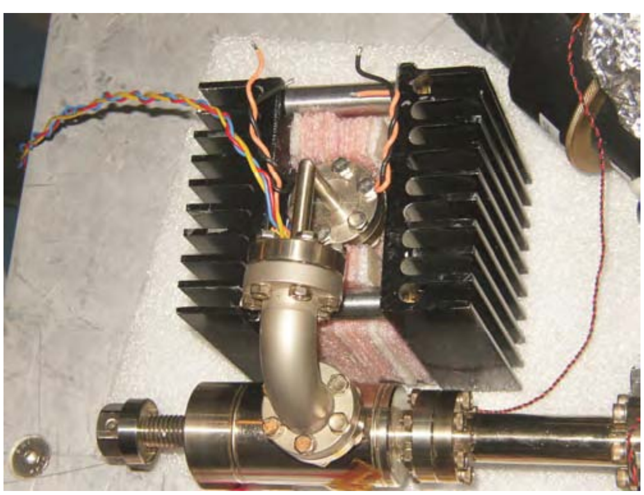

Fig. 5 — Cs source assembly integrated with the octagonal cooling chamber of physics package of Cs fountain

2.3 Lock-in amplifier

Precise control of temperature depends upon accuracy of measurement of error signal which is the difference of set-point temperature and actual measured temperature. A lock-in amplifier detects signal of the order of few nanovolts buried in noise sources many times larger than the signal itself by a technique known as phase sensitive detection[5,6] (PSD). Fig. 7 is the block diagram and the details of the circuit are shown in the schematic Fig. 6 of temperature controller. Different stages of lock-in amplifier are described below:

As shown in Fig. 7, it has a low frequency sine wave reference source which excites a AC Wheatstone bridge as well as a phase shifter to generate error and detection signals at the same frequency. The circuit of Wheatstone bridge is shown in Fig. 8. AC excitation of the bridge has another advantage that it eliminates amplifier offsets, drifts and parasitic thermocouple effects due to components and wiring of the board[12]. The error signal i.e the output of Wheatstone bridge is amplified with a gain of 100 to make it suitable for the phase sensitive detector.

The reference trigger generates two rectangular detecting pulses at the reference frequency and the phase shifter is used to fine tune the zero phase difference between error signal and reference triggers.

In the phase sensitive detector, the error signal is detected at the reference frequency and phase. The output of phase sensitive detector has two components having frequencies (f_1+f_2) and ((f_1–f_2). As the frequency and phase of reference source and error signals are the same, the output has two components at $2f_0$ and at *dc* or zero frequency. Both these outputs are proportional to the error signal[5].

The second order narrowband low pass filter eliminates the second harmonic component and also the random noise present in the output of the phase sensitive detector. The output is true *dc* and is proportional to the error signal. This output is given to PID controller. Fig. 9 shows the output of phase sensitive detector and low pass filter before the temperature has stabilized.

2.4 PID Controller

PID controllers were first introduced in the market in 1939 and have remained the most widely accepted closed loop servo controlled techniques for process

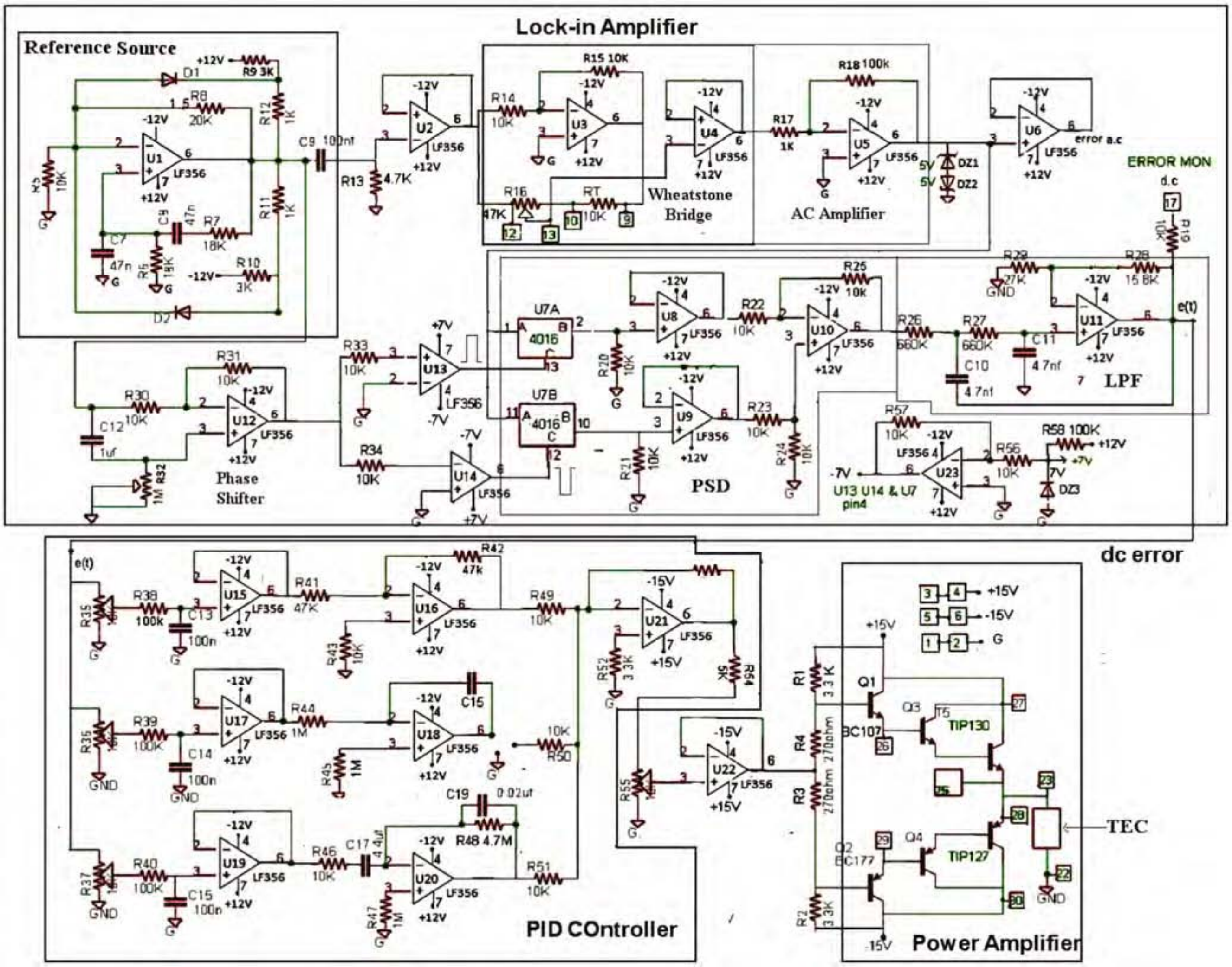

Fig. 6 — Schematic of temperature controller

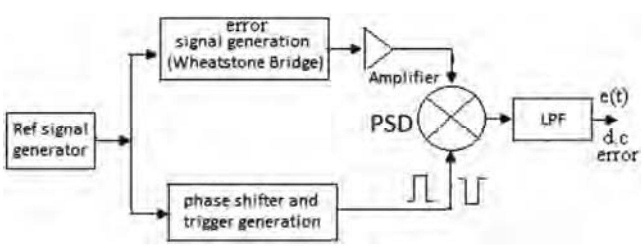

Fig. 7 — Block diagram of lock-in amplifier

control until today[7-10]. The block diagram of PID controller is shown in Fig. 10. Unlike on-off type control where the load is supplied either maximum power or no power with some hysteresis, in PID controller the temperature of the module follows the set point temperature. The error voltage which is the difference of desired set point temperature and actual measured temperature, is generated in a Wheatstone bridge (Fig. 8). Potentiometer P sets the desired

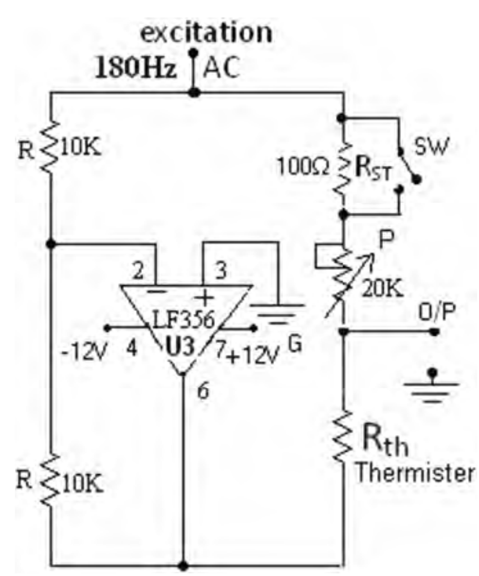

Fig. 8 — Wheatstone bridge

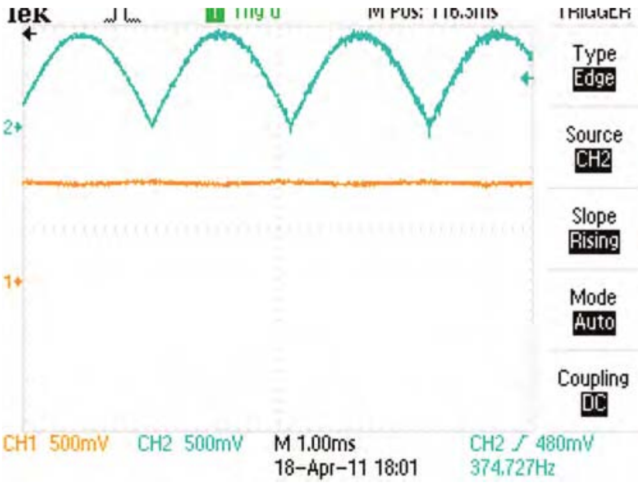

Fig. 9 — Error signal after PSD (blue trace, o/p of U10) and after LPF (orange trace, o/p of U11)

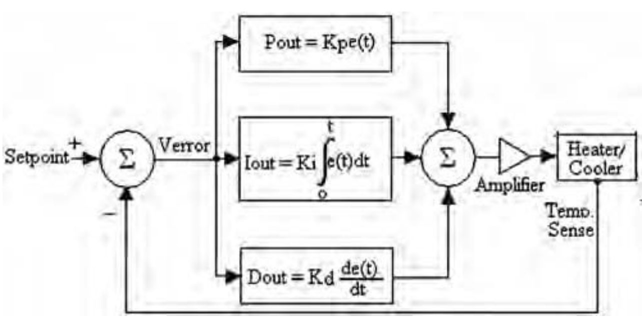

Fig. 10 — Block diagram of PID controller

temperature and actual temperature of the Cs source is sensed by a precision thermister R_{th}. The error voltage is multiplied by proportional, differential and integral gains and the sum of these three parameters is applied to the process after amplification. When these three parameters are properly tuned the controller gives exceptional control stability. Mathematically PID output can be expressed by the following equation.

PID output = $P_{out} + L_{out} + D_{out}$

$$= K_p \cdot e(t) + Ki \cdot \int e(t)dt + Kd \cdot de(t)/dt \qquad \ldots(1)$$

where e(t) = instantaneous value of error voltage

= set-point-feedback reading (measured value)

*K*p: Proportional gain

*K*i: Integral gain

*K*d: Differential gain

A brief description of each type of control is given as:

2.5 Proportional control

The first term in Eq. (1) is proportional term and reduces a large part of the overall error. If the proportional gain is too high the system becomes unstable and if it is too low the output response is very small corresponding to large input errors. Thus,there remains a steady state error and the target value is never reached.

2.6 Derivative control

The rate of change of controller output is decided by the derivative action. This helps in reducing overshoot and ringing caused by proportional and integral action.

2.7 Integral control

The contribution from this term is proportional to both the magnitude of error and duration of error. It accelerates the process towards set-point and eliminates steady state error. If the integral gain is high the output may cross the set-point and give an overshoot. The schematic of the PID controller is shown in Fig. 6. The output of this circuit is given to the power amplifier.

2.8 Performance evaluation of PID controller

The controller is evaluated by unit step set-point response. As shown in Fig. 8, a 100 Ω resistance with a toggle switch is connected in series with the set-point potentiometer. Inserting or removing the resistance causes a step change of about 0.3°C in temperature. The most popular and widely used PID Tuning methods are John Shaw's (Ziegler-Nichols Based) method and CDHW method[11], If the process time constants are known, the best controller settings can be calculated and directly implemented otherwise the controller can be tuned by trial and error method in a closed loop mode. We followed CDHW method for tuning the controller. Figs 12-15 show the response of controller for proportional, differential and integral gain settings for best performance of the controller corresponding to a step change in temperature. The setting may change from process to process depending upon their time constants. It is very important that response needs to be not too oscillatory, but converge to a constant value for stability of the control system.

2.9 Power Amplifier

The power amplifier (Fig. 6) is built with one pair of complimentary power darlington transistors TIP122(NPN) and TIP127(PNP), each rated for V_{ceo}=100V I_c=5A, and h_{fe} (minimum)=1000 and one pair of driver transistors BC107(NPN), BC177(PNP). The output of this driver circuit which swings from-12V to +12V is connected to the Peltier devices in the Cs module.

The display is taken before stabilization of temperature, hence the error signal is large.

2.10 Temperature Display Circuit

We have used K type thermocouple and thermocouple signal conditioner IC AD595 manufactured by Analog Devices[13] for measuring and displaying the temperature of Cs Source. The thermocouple is firmly attached with the Al block holding the Cs ampoule.

Figure 11 shows circuit diagram of display circuit. The Seeback voltage generated in a thermocouple circuit is directly proportional to the difference of temperature between the two junctions. Therefore to determine the temperature of measuring junction the temperature of the reference junction must be known.

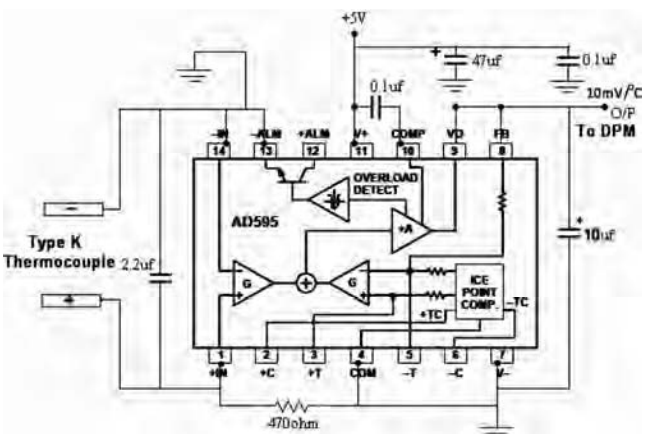

Fig. 11 — Thermocouple signal conditioning circuit for displaying temperature of Cs ampoule

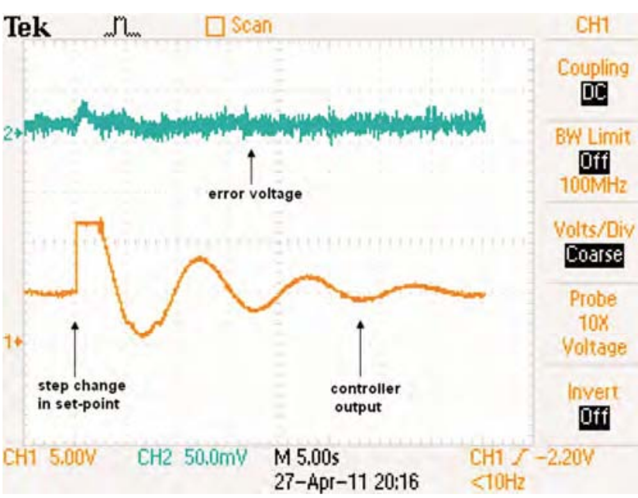

Fig. 12 — Transient response of controller with step change in set-point temperature when $K_P = P$ (gain K_p is increased until oscillations start), T_D=0, T_I=∞. Due to high gain the error voltage is very small (≈15mV). Period of oscillations = 11s

AD595 provides cold junction compensation by adding a voltage into thermocouple loop that is equal and opposite of the reference junction. The reference junction is formed at the interconnection of thermocouple leads and the IC pins. The output of the circuit is 10 mV/°C and is scaled to 1 mV/°C in the DPM circuit for displaying the temperature. Temperature measured with the signal conditioning circuit developed was calibrated against a standard Fluke digital thermometer and the measurement error was within 0.5°C.

3 Discussion and Conclusions

A detailed description of the design details of atomic flux controller for Cs source is reported in this

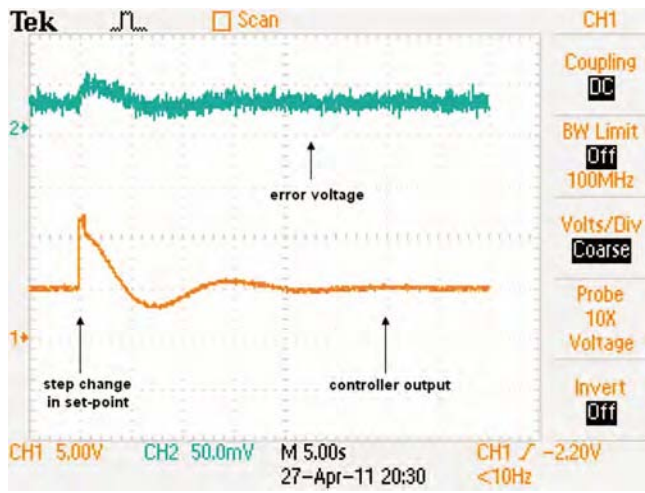

Fig. 13 — Transient response of controller with step change in set-point temperature when K_P =0.7P, T_D=0, T_I=∞. Decrease in gain increases error voltage from 10 mV to 30 mV

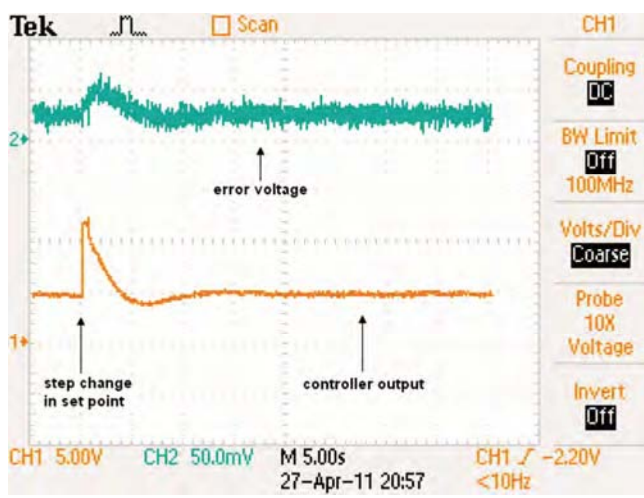

Fig. 14 — Transient response of controller with step change in Set-point temperature when K_P =0.7P, T_D=3.5s, T_I=∞

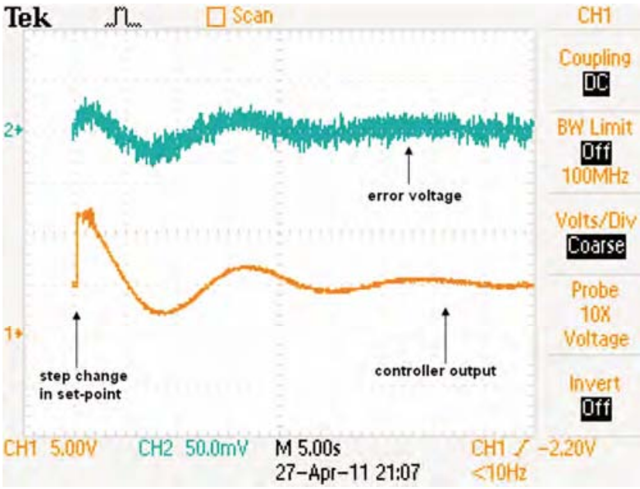

Fig. 15 — Transient response of controller with step change in set-point temperature when K_P =0.7P, T_D=3.5s and T_I =5.5s (Integral gain is increased until error voltage is equal to zero). The output settles to the new set-point which is 0.3ºC below the previous set-point in 40s.

paper. The control of atomic flux is important to provide and maintain optimum vapour pressure inside the trapping chamber. The ampoule is attached to the main system which is continuously pumped to avoid buildup of hydrogen and helium vapour, it is necessary to have a constant source of Cs with a flux (temperature) controller in order to maintain the correct pressure. At those times when the experiments are held-up, it is important to cool the Cs source well below the room temperature. Then the source is kept at 10°C, the minimum which can be maintained with our temperature controller. The temperature of the Cs ampoule cannot be lowered below 10°C due to limited space available for the cooling module in the fountain set-up. To lower the temperature further, either a large heat sink is required or other options like forced or liquid cooling have to be adopted. However, we preferred to keep the minimum temperature to 10°C rather than using fans which generate EMI or liquid cooling which requires another component like a heat exchanger.

If one starts with an evacuated chamber or opens the valve of the Cs source to the chamber after a long time, initial supply of the Cs will get adsorbed on the walls. At those times, one needs to heat the Cs source to 80°C for long time before one can see some fluorescence from Cs atoms inside the chamber. During continuous experimental runs, the temperature of the ampoule is kept at 10°C at night and is raised in the morning before starting the trapping experiments. Once the temperature is raised to 40°C from 10°C, the Cs vapour comes to equilibrium pressure with a time constant of 8 min. When the temperature is turned down to 10°C again, the vapour pressure drops with a time constant of 5 min. The temperature is maintained with accuracy better than 0.1°C.

After integrating the two stage Cs cooling module with the octagonal chamber we are able to maintain the temperature of Cs ampoule anywhere between 10° to 80°C with accuracy better than 0.1°C which is acceptable for operating the Cs fountain. The maximum power dissipated in the circuit is less than 20W. The highest temperature (80°C) possible with the module is limited due to power supply used for the cooling module. This high temperature is rarely needed and is sufficient for our requirement. As shown in Figs 12-15, the overall response of the controller is quite stable and reliable.

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