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ACCELERATOR / AVERAGER CIRCUIT CONTROLS THE RESPONSE TIME OF THERMOPILES

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Thermal methods for laser radiometry are today the most used. Unfortunately, they are slow. Fortunately, this draw-back can, in some cases, be overcome electronically. The paper presents a detailed way to do this for thermopiles. The response analysis is performed for two circuit versions. Experimental data are presented for a medium-power thermopile, followed by one of the circuits. The system is part of the first Romanian digital powermeter for lasers (third version).

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1. Introduction

Thermopiles are maybe the most used sensors for cw laser radiation optical power measurements. Unfortunately, they are slow, especially the types for high power (response times up to tens of seconds). For a large number of measurements or monitoring fluctuating laser optical power, this feature is a clear draw-back. Fortunately, the response time of the powermeter can be shortened electronically, in respect with the value belonging to the thermopile alone. The paper reports a circuit having this function. The reported circuit also reduces noise in the thermopile response.

It is worth mentioning that many modern and expensive laser powermeters, manufactured by well-known specialized companies, do *not* have response time shortening (ex.: Rm-3700 [1], and also the more complex Rm-6600 [2], both manufactured by Laser Probe, Inc. – USA, which is, since several years, the new name of the well-known Laser Precision, Inc.). Older thermopile analog laser powermeters like Coherent Radiation Model 201 (USA) also used simple circuitry for response time shortening, but the dedicated circuit was a PD (Proportional-Derivative) controller [3], which is noisy, as it will be explained in this paper. There are also modern powermeters [4], [5] which have "anticipation" of the thermopile response, but these are microprocessor instruments and the "anticipation" is performed by software for several thermopile models accomodating each monitor. So, they are complicated and expensive. There are still analog powermeters too [6], accomodating several "intelligent" thermopiles via personalised modules (for each thermopile), and these modules should contain "anticipation" hardware, probably similar to the reported circuit. Anyway, the "anticipation" hardware and software are *by no means* revealed by the manufacturers, since they usually are proprietary solutions. Handbooks for such instruments (either microprocessor-driven or simply analog) do **not** usually contain electrical schematics any more (like for older ones).

This is probably the first published detailed analog hardware solution for the mentioned problem. The author has browsed the collections for several years of the following journals: Review of Scientific Instruments, Measurement Science and Technology, International Journal of Optoelectronics. He has found no paper dealing with this problem.

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2. Accelerator / averager circuit versions and response analysis

A circuit which controls the response time of a laser powermeter can be implemented using only one operational amplifier. Its function is switched by a front panel switch (accelerator / averager). As an accelerator, it shortens the response time of the whole powermeter (i.e. thermopile + readout unit), in comparison with the response time of the thermopile alone. As an averager, it acts contrarily.

For this circuit, the most straightforward idea is to use a common PD (Proportional Derivative) controller. Such a circuit is used in automated control analog systems. Its typical structure is shown in Fig. 1.

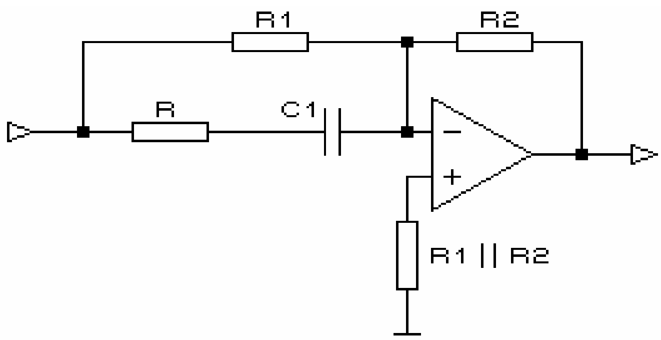

Fig. 1. Common PD controller.

Using the Laplace transform, its transfer function can be easily found:

$$H(s) = -\frac{R_2}{R_1} \cdot \frac{1+\tau_1 s}{1+\tau' s} \tag{1}$$

where $\tau_1 = (R_1 + R)C_1$ and $\tau' = RC_1$.

One can assume that, for a step input (of light power), the thermopile response is exponential (this was experimentally proved to be a good assumption [7], [8]), having the normalised form:

$$v_i(t) = 1 - \exp(-\frac{t}{\tau}) \tag{2}$$

where τ is the thermopile time constant. The Laplace transform corresponding to (2) is expressed as:

$$V_i(s) = \frac{1}{s(1+\tau s)} \tag{3}$$

By using the Laplace transform [9], [10], it can be immediately shown that, if the condition:

$$\tau_1 = \tau \tag{4}$$

is accomplished, the output of the circuit is expressed as:

$$v_o(t) = L^{-1}\{\ H(s)V_i(s)\ \} = -\frac{R_2}{R_1}\left[1 - \exp(-\frac{t}{\tau'})\right] \tag{5}$$

Since $\tau' < \tau_1 = \tau$, it can be seen that the response of the circuit is faster in comparison with the thermopile alone. The condition (4) can be accomplished by simply tuning R_1 (there is no trimmer for the large value of C_1). Later a tuning procedure will be described.

As the derivative component of the controller is inherently noisy, a noise analysis must be done. The most straightforward way to test how noisy the circuit can be is to evaluate its response to a step input (this approximately corresponds to pop-corn noise generated by the amplifier which precedes the PD controller). The response to a normalised step input can be immediately calculated for $t = 0$:

$$v_o(0) = -\frac{R_2}{R_1 \| R} \tag{6}$$

It can readily be observed that:

$$|v_o(0)| > |v_o(\infty)| = \frac{R_2}{R_1} \tag{7}$$

The mentioned input and corresponding output signals are depicted in Fig. 2.

So the circuit amplifies step-like noise which can possibly be generated by an input amplifier, which precedes the PD controller. A simple method to avoid this is to place a feedback capacitor C_2 in parallel with R_2. In this case, it is obvious that $v_o(0) = 0$ (as both C_1 and C_2 behave like short-circuits for $t = 0$). Actually, this modified circuit is a sort of PID controller (Proportional Integrating Derivative). The input and output signals for this circuit are depicted in Fig. 3. Increasing C_2 transforms the circuit into an averager (with a time constant higher than the thermopile alone). A detailed behaviour analysis for this modified circuit will not be performed here, because another structure has been chosen – Fig. 4.

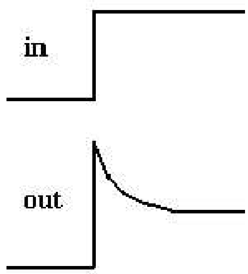

Fig. 2. Output of a PD controller to a step input.

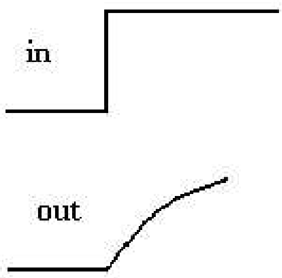

Fig. 3. Output of a PID controller to a step input.

Placing a low-pass filter in front of the circuit became thus possible by adding only one resistor and one capacitor C. This filter was necessary because of the input amplifier high input resistance (non-inverting configuration) and medium internal thermopile resistance (some kΩ), both leading to some 50 Hz (hum) noise pick-up (which could decrease the readout stability for low or 0 input optical power levels). A more detailed analysis of this circuit will be performed here. For the sake of simplicity, capacitor C will not be taken into account in this analysis, but some considerations about its influence will be made afterwards.

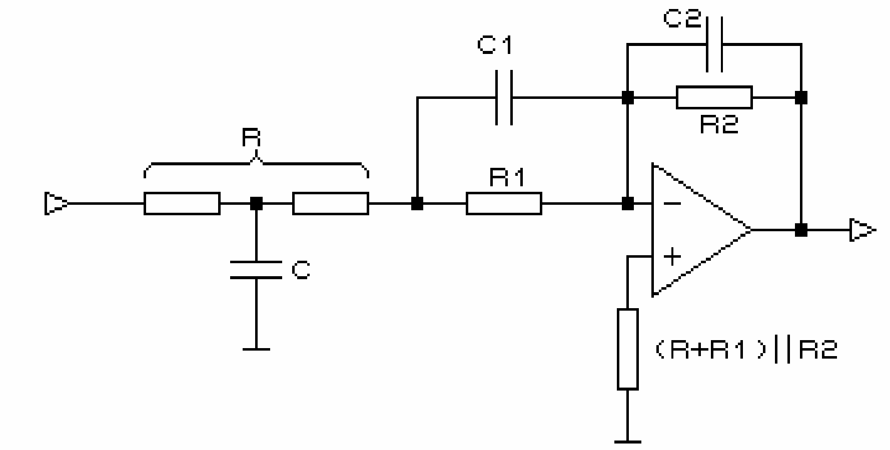

Fig. 4. Structure used for the thermopile signal accelerator / averager circuit.

The transfer function of the circuit is expressed as:

$$H(s) = -\frac{R_2}{R_1 + R} \cdot \frac{1+\tau_1 s}{(1+\tau_2 s)(1+\tau' s)} \tag{8}$$

where $\tau' = (R_1 || R)C_1$, $\tau_1 = R_1 C_1$ and $\tau_2 = R_2 C_2$.

For the input (2) and the corresponding Laplace transform (3) the output of this circuit is expressed as:

$$V_o(s) = V_i(s)H(s) = -\frac{R_2}{R_1 + R} \cdot \frac{1+\tau_1 s}{s(1+\tau s)(1+\tau_2 s)(1+\tau' s)} \tag{9}$$

With the conditions $\tau_1 = \tau$ and $\tau' \neq \tau_2$ the corresponding time response is expressed as:

$$v_o(t) = -\frac{R_2}{R_1 + R}\left[1 - \frac{\tau_2}{\tau_2 - \tau'}\exp(-\frac{t}{\tau_2}) + \frac{\tau'}{\tau_2 - \tau'}\exp(-\frac{t}{\tau'})\right] \tag{10}$$

For $\tau' << \tau_2$, (10) becomes a simple exponentially increasing function:

$$v_o(t) \approx -\frac{R_2}{R_1 + R}\left[1 - \exp(-\frac{t}{\tau_2})\right] \tag{11}$$

To summarise, using this circuit one can change the time constant τ of the thermopile alone by another time constant τ_2, provided that $\tau_1 = \tau$ and $\tau' << \tau_2$ (this last condition can be easily accomplished for low R values in comparison with R_1 and R_2). The noise test for this circuit, performed with a step input at $t = 0$, shows that $v_o(0) = 0$ (Fig. 3). This circuit is some sort of a PID controller.

It is essential to see how the condition $\tau_1 = \tau$ can be accomplished. With the assumption that $\tau' << \tau_2$, (9) becomes:

$$V_o(s) \approx -\frac{R_2}{R_1 + R} \cdot \frac{1+\tau_1 s}{s(1+\tau s)(1+\tau_2 s)} \tag{12}$$

The corresponding time response is expressed as:

$$v_0(t) \approx -\frac{R_2}{R_1 + R}\left[1 + A\exp(-\frac{t}{\tau}) + B\exp(-\frac{t}{\tau_2})\right] \tag{13}$$

where $A = \dfrac{\tau_1 - \tau}{\tau - \tau_2}$ and $B = \dfrac{\tau_2 - \tau_1}{\tau - \tau_2}$.

There are three possible situations for A and B: 1. $A < 0$ and $B >$ -1 for $\tau_2 < \tau_1 < \tau$;
2. $A = 0$ and $B =$ -1 for $\tau_2 < \tau_1 = \tau$;
3. $A > 0$ and $B <$ -1 for $\tau_2 < \tau < \tau_1$.

The outputs of the circuit corresponding to the situations 1-3 are presented in Fig. 5.

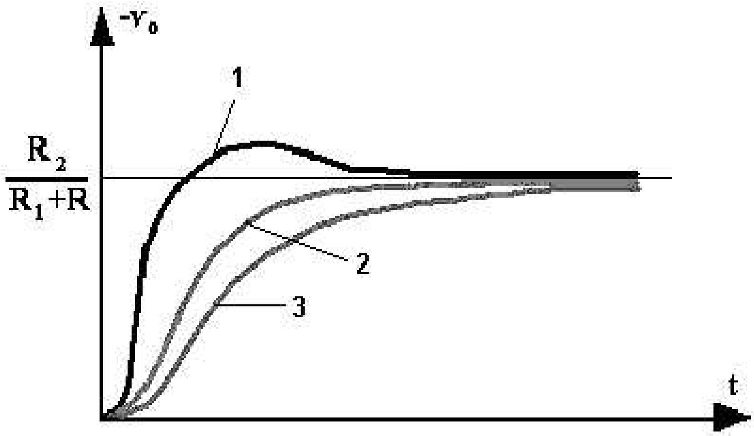

Fig. 5. Time behaviour of the used circuit in situations 1-3, for an exponential input signal with τ .

τ_1 is changed by tuning R_1 till the fastest response with no overshoot is obtained (curve 2). This tuning can be easily performed only looking to the display of the powermeter and applying step-input optical power on the thermopile, or using an oscilloscope. In the optimal situation 2 the output (11) was thus found again. Unfortunately, by tuning R_1 the gain of the circuit is changed, so this time constant matching must be performed *before* the calibration of the powermeter. Since the "speed" of the thermopile does not change in time, the circuit must be tuned only once.

As τ_2 is completely independent of all other time constants, it can be either smaller than the thermopile time constant, the circuit acting in this situation as a response accelerator ($\tau_2 \approx$ 0.3 s), or higher, the circuit thus acting as an averager. The second situation is easily obtained from the first one by simply connecting a higher value capacitor in parallel with C_2 using a front panel time response switch. Capacitor C, which was not considered in the calculus, increases just a little the time constant τ which is "seen" by the circuit. The cutoff frequency of the low-pass (LP) filter in front of the circuit is about 5 Hz, so it has a time constant of 32 ms. Compared to the thermopile time constant $\tau_{thermopile}$ = 1.7 s (which corresponds to a t_{resp} = 4 s (14)), the LP filter time constant "slows down" insignificantly the total response of the signal at the input of the accelerator/averager circuit, so initially neglecting C proves now to be a good assumption. The response time t_{resp} is usually measured on the oscillogram between 0 and 90% of the stationary response to a step input and, for exponential response (2) it is connected to τ by:

$$t_{resp} = 2.3\tau \tag{14}$$

3. Experimental results and discussion

The two time values of the 0-90% response to step optical power were set to about 1 second (FAST position of the time response switch) and 8.2 seconds (AVG), while having 4 seconds for the thermopile alone. In the FAST regime, the theoretical minimum limit for the response time of the system is about 0.7 seconds (as given by τ_2 and (14)), but tuning the circuit for a slightly higher value was preferred, since a small amount of averaging reduces noise.

Several response signals were acquired, saved and printed, using an Agilent 54820A Infiniium digital oscilloscope and the graph editor Origin 6.1. In Figs. 6 and 7, both the signal response of the thermopile alone (type Laser Probe RkT-30 CAL) and using the accelerator / averager circuit are plotted, for a step-input laser beam. Supplementary, in Fig. 8 a pulsed (chopped) laser input is plotted (acquisition via a photodiode), just to see the circuit behaviour in the "averager" structure. In all the mentioned figures Channel 1 represents the response of the thermopile alone, and Channel 2 – the response of the system thermopile + circuit.

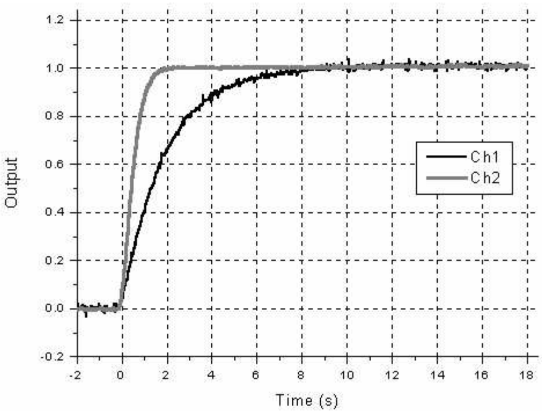

Fig. 6. Circuit having the "accelerator" structure.

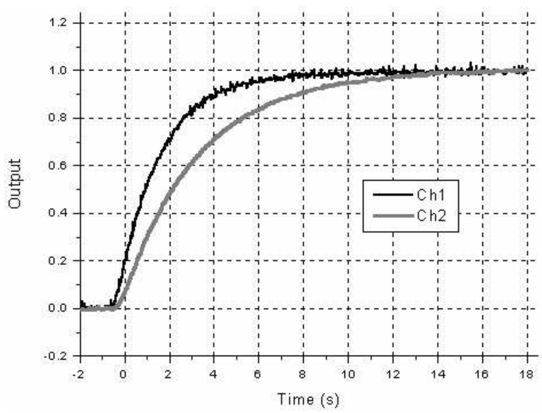

Fig. 7. Circuit having the "averager" structure.

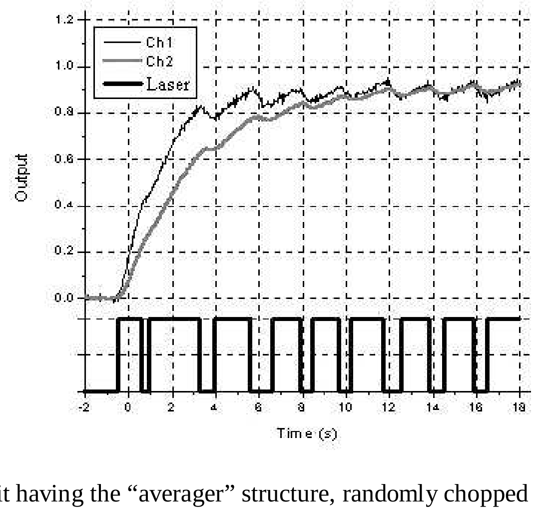

Fig. 8. Circuit having the "averager" structure, randomly chopped cw laser beam.

In Fig. 6 the faster response of the system thermopile + circuit (channel 2) can be seen, compared with the response of the thermopile alone (channel 1), just as theoretically predicted. For an easy comparison, the responses are both normalized. In Figs. 7 and 8 the slower response of the system thermopile + circuit is remarked, compared with the response of the thermopile alone.

A low drift operational amplifier was used for the accelerator / averager circuit (the common type LM 308 A), and a multi-turn trimming potentiometer for setting the value of τ_1. The circuit is part of a home-made digital powermeter for lasers [11].

4. Conclusions

A comparison is worth to mention between the response times for Laser Probe Rm-3700 (owed by the laboratory where the author works), and for the more complex Rm-6600 (tested by the author) – on one side, and for the home-made powermeter – on the other side. For any used thermopile, the shortest response time available of the mentioned Laser Probe powermeters equals that of the thermopile alone - 4 seconds for RkP-30CAL, used by the author, but only 1 second for the home-made powermeter [11], which includes the accelerator circuit. This powermeter also performs in a much easier manner laser power *averaging*, by turning the circuit which controls the response time into an analog averager. This change is performed by simply connecting a supplementary capacitor in the feedback loop of the operational amplifier used, with a front panel switch. The advantage of such a simple system (besides the simplicity itself) consists in *permanent* updating of the displayed average power value, while the time between value updating for the software ones (used by all microprocessor-driven powermeters) usually depends on the selected number of samples to be averaged and on the sample rate.

To the knowledge of the author, this is the first published systematic research on this problem. The reported circuit is original concerning its schematic, although it has the behaviour of a PID controller, and also concerning the analysis of its functioning. PID controllers used in automatic process control are generally analysed only for step input signals, while the analysis presented in the paper is performed for exponential input signals, specific for thermopiles.

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