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Dynamic digital registration of a section of the spectrum in the optical range

A.A. Popov[1,*], *A.F. Kokorin*[1]

[1]*Ural Federal University, Yekaterinburg, Russia*
[*]*slymbe@yandex.ru*

Abstract. To be able to analyze the dynamics of some physical processes, such as the destruction and evaporation of meteorite matter from its surface during simulated flight in the Earth's atmosphere, a system for recording optical spectra in digital format with high time resolution was developed. The system is based on the decomposition of optical radiation into a spectrum using an optical prism spectrograph, subsequent fixation of images of a section of the spectrum on a CCD array and analysis of the resulting spectra. The use of a CCD sensor reduces the exposure time, which increases the frequency of recording spectra. Automated software image analysis makes it possible to determine the dependence of the relative intensity of radiation on wavelength (spectral characteristics) or on time (process dynamics). The analysis is based on determining the spectral lines in the image from the peaks of the dependence of the brightness of the pixel section on its position and comparing the brightness of the pixel, the charge in the CCD array element and the intensity of incident radiation. Based on the results of the work, the dependences of the relative intensity of radiation on the wavelength for the stationary spectrum and the dependence of the relative intensity of a single spectral line on time are obtained.
Keywords: optical spectroscopy, image analysis, dynamic registration.

1. Introduction

One of the most common types of material composition research is spectral analysis. Atomic emission spectral analysis is most often used, which makes it possible to determine the chemical composition of a substance by the radiation spectrum of its atoms under the influence of an excitation source. Sources of excitation can be arcs, spark, flame or plasma. Studies of heat-shielding and ablative materials are often carried out using plasma [1], as well as experiments on modeling the passage of the Earth's atmosphere by cosmic bodies [2–4]. These studies are aimed at identifying elements that break down and evaporate from the surface of the material under the influence of heat flow.

Spectral analysis with high time resolution is particularly informative, it allows you to see changes in the spectrum occurring in short periods of time, in other words, to track the dynamics of the ongoing process. To achieve this result, it is necessary to use a device with a high frequency of spectrum fixation.

In this paper, we consider the creation of a prototype system for dynamic digital fixation of optical spectra, as well as the development of an algorithm for software analysis of the images obtained.

2. Experimental setup

To decompose the radiation into a spectrum, devices with a dispersing element are used, which separates the radiation into components according to wavelengths. A prism or diffraction grating is most often used as such an element. The ISP-51 optical prism spectrograph was used in this work. The initial design of the spectrograph assumes the use of photographic plates for fixing spectra, which, due to the long exposure time, does not allow tracking changes in the spectrum occurring during the exposure of the photographic plates. To increase the frequency of recording spectra, the camera for photographic plates was replaced with a CCD camera. This solution also made it possible to obtain images in digital format, which makes it possible to simplify the subsequent storage, transmission and analysis of data.

3. Image Analysis

To obtain analytical information from the images of the spectrum section, software was developed within the framework of this work. It is based on obtaining and analyzing data on the brightness of pixels in the spectrum image. Given the proportionality of the pixel brightness to the charge accumulated on the CCD array element and the proportionality of the accumulated charge to the intensity of incident radiation, it is possible to switch from the pixel brightness scale to the relative radiation intensity. This allows you to analyze the dependence of the relative intensity on the pixel position. To move from the pixel scale to the wavelengths, it is necessary to calibrate using spectra with known spectral lines. While maintaining the conditions of the experiment, after calibration we get the conversion factor of pixels into wavelength. After calibration, we have a dependence of the relative radiation intensity on the wavelength, thereby obtaining a convenient representation of the radiation spectrum for analysis.

Spectral lines are recognized by detecting intensity peaks on the spectrum. By the wavelengths of the recorded lines and their relative intensity, it is possible to judge the composition of the gas formed at the surface of the material, which is the source of the analyzed radiation.

In the case of using a CCD sensor as part of digital cameras, the RAW format should be used to avoid introducing additional errors due to internal image processing during shooting. It is also necessary to take into account the spectral sensitivity of the CCD matrix itself, in order to obtain more accurate data on the radiation intensity, CCD matrices with a known sensitivity dependence should be used and taken into account in software image processing. In this paper, the initial stage of testing this type of research is considered, therefore, the spectral sensitivity of the CCD matrix used is not considered in the examples. In further studies, it is planned to use a CCD sensor with known sensitivity parameters.

3.1. Process dynamics

Of particular interest is the dynamics of various processes. To observe it, it is necessary to capture images of the spectrum with a certain frequency. With this analysis, the spectral line of interest is selected in this work, and then the change in its intensity in images taken at certain intervals is estimated. The dependence of the relative intensity on time obtained in this way serves as a characteristic of the process over time. For example, during tests on the destruction of heat-protective materials or ablation of meteoroids, it is possible to observe changes in the evaporation intensity of certain elements that make up the structure from the surface of the material depending on the time of exposure to heat flow. Such studies can help to improve thermal protection systems and simulate the destruction of meteoroids.

An additional obstacle in the case of such studies is the difficulty of building an optical system in such a way as to “cut off” the radiation of a heated solid representing a continuous spectrum. To solve this problem, it is planned to use filters at the entrance slit of the spectrograph in the future to “cut off” the radiation of a solid from the radiation of an evaporating gas.

4. Results

In the course of the work, images of the spectra of several gas-discharge lamps were obtained. The obtained spectra of mercury and fluorescent lamps are shown in Figs. 1–2.

The spectrum of the mercury lamp was used to calibrate the system, after which the spectrum of the fluorescent lamp was investigated. The results are shown in Figs. 3–4.

Dynamic spectrum analysis has produced images with a time resolution of 200 ms, which makes it possible to analyze the processes of destruction and evaporation in the heat flow. The dynamics of the intensity of the red line radiation in the spectrum of a fluorescent lamp was studied experimentally (Figs. 5–6).

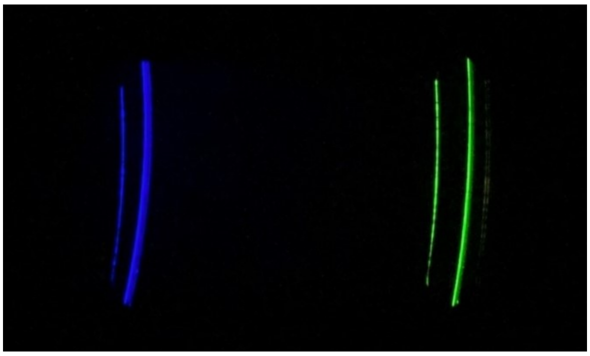

Fig. 1. The resulting image of a section of the mercury spectrum.

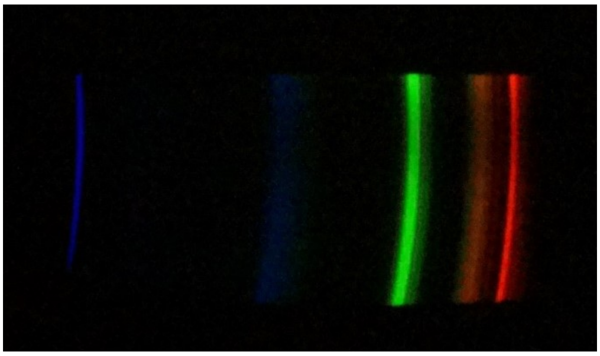

Fig. 2. The resulting image of a section of the spectrum of a fluorescent lamp.

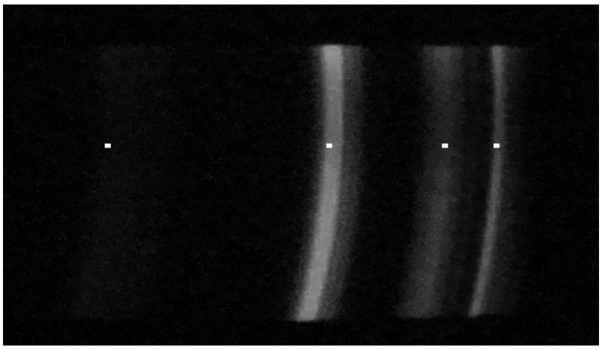

Fig. 3. Visual display of the found spectral lines.

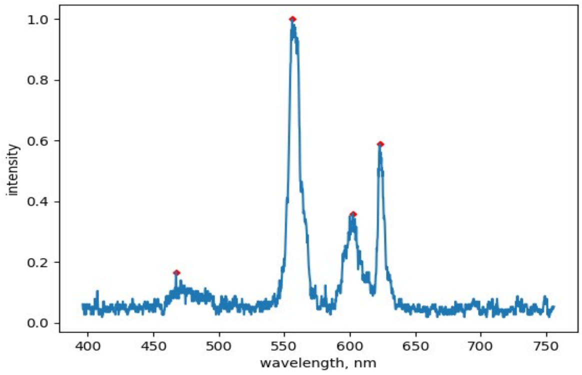

Fig. 4. The obtained dependence of the relative intensity on the wavelength.

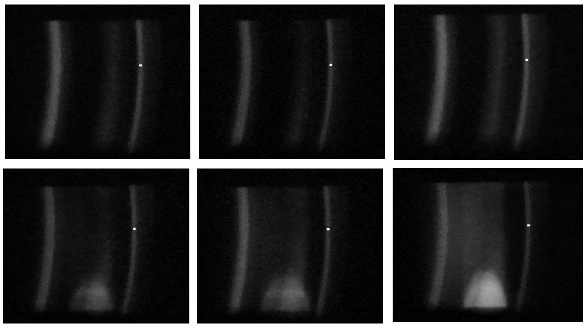

Fig. 5. Observation of a part of the spectrum of a fluorescent lamp with a period of 200 ms.

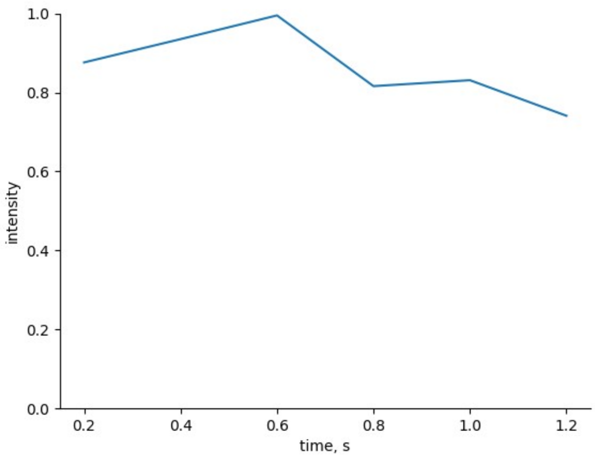

Fig. 6. The dependence of the relative intensity of the red line in the spectrum of a fluorescent lamp on time.

5. Automation of installation

In order to automate experiments on the study of emission spectra, an auxiliary device has also been developed in the course of this work, which is a software-controlled stepper motor with error correction. The task of this device was to shift the output part of the spectrograph spectrum in accordance with the selected spectral region for analysis. The parameters were set in the user interface on the PC and transmitted to the microcontroller via the serial port. Error correction was carried out by comparing the actual number of revolutions of the stepper motor, which was monitored by the rotation sensor, and the set number of revolutions. The set amount is calculated by

MK as the number of revolutions necessary to shift the output part of the spectrum, so that the wavelength specified in the user interface is in the center of the output part of the spectrum. To determine the dependence of the rotation of the shift knob of the spectrum on the wavelength of the line located in the center of the output part of the spectrum, calibration was performed using the spectrum of neon and mercury lamps.

6. Conclusions

The developed prototype allows you to obtain digital images of a section of the spectrum, and the developed software converts images depending on the relative intensity of the wavelength at a certain point in time or depending on the relative intensity of time for a fixed wavelength. The research is in its initial stages. In the future, it is planned to add accounting for the spectral sensitivity of the CCD matrix used. This system will be used in a series of experiments to determine the composition of the gas formed during the destruction of heat-shielding materials in a heated gas stream and modeling the ablation of meteoroids to track the dynamics of evaporation of certain elements from the surface of the material under the influence of heat flow.

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