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Spectral Analysis Using a New Opto-Mechanical Instrument

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Abstract: Design and operation of an opto-mechanical system for spectral analysis using a double fiber design for light delivery are reported in this study. A simple mechanical drive system is used, which is able to perform a fine course of angular motion for the scanning of the dispersive optical element. The presented system consists of a mechanical drive system, a dispersive element, a double fiber assembly and a photodetector. A source light, a digital multimeter and a PC are used to test the presented design. The first-order diffraction of the white light source is obtained by using a reflection diffraction grating in Littrow arrangement. By comparing the output reflection signals of the plane mirror and plane grating it is concluded that the output signal is related to the first-order diffraction rather than zero order, which corresponds to that of the plane mirror. In another test a holographic grating is used in place of the ruled grating and the first-order diffraction is resolved for this grating. The groove number for the ruled grating is 1370 g mm^{-1} where the first-order diffraction angle is about 20° while for the holographic grating with 1200 g mm^{-1} the first-order diffraction angle at similar wavelength is about 17.45°.

Key words: Design, fiber, grating, mirror, mechanical scanner

INTRODUCTION

In many applications there is a need for a system, which is capable of analyzing the source or emitted light spectrum. For instance instruments such as monochromators and spectrophotometers are used widely in the field of optical, IR and UV spectroscopy need such a wavelength selection system. Another area of interest has been in laser and dye laser systems to produce a tunable light for a wider range of electromagnetic spectrum. Other applications are in the atomic absorption/emission spectroscopy, which requires such a system for producing monochromatic light and wavelength analysis. In optical communication such a method can be used in Wavelength-Division Multiplexing (WDM) and demultiplexing techniques in order to displace or combine carrier signals with different wavelengths containing different bits of information (Maier *et al*., 2003; Li *et al*., 2008; Pérez-Millán *et al*., 2007; Dai *et al*., 2007; Zhu *et al*., 2006). Basic structure of a grating demultiplexer includes a fiber carrying light including wavelengths, λ_1 ... λ_n, an expanding and collimating lens, a reflection grating and another lens to focus different wavelengths at separated positions (Romero *et al*., 2005; Wen *et al*., 2004; Song *et al*., 2003; Matos *et al*., 2007; Su and Huang, 2007). Different versions such as GRIN lens grating, Littrow-configured grating and Concave mirror grating are reported for this purpose (Allard and Fiber, 1990). In related study Xu *et al*. (2008) reported analysis of spectral characteristics for reflective tilted fiber gratings of uniform periods. The reported system is therefore can be implemented for the development of new optical instruments such as described in which wavelength selection and separation are required.

A system using optical fibers for light delivery to perform high resolution multiobject spectroscopy is reported by Szentgyorgyi (2006). For wavelength selection and scanning operation (Golnabi, 2000) angular scanning of the dispersive element is required. To scan the angle a mechanical scanning unit is required for such systems. For instance, for scanning operation stepper motor driver system can be used for angle scanning. Precision rotation stages are now manufactured, which are ideal for fine-tuning angular orientation of any component. When a 800 step/turn motor is used it is possible to find an angular resolution of about 0.45°. As can be seen the direct scanning of the optical element with such a rotation stage provides a low resolution. Using a similar stepper motor (800 step/turn) to drive the mechanical drive stage the resolution of such a system can be improved and the reported system provides a high scanning resolution of (0.5 mdegree/step). With the help of a high resolution dispersive element it is possible to have a high resolving power at higher diffraction orders that makes the optical instrument a unique one.

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MATERIALS AND METHODS

This study was conducted in Institute of Water and Energy a research center of Sharif University of Technology during period of 2006-2008. Figure 1 shows the general arrangement to test operation of the reported system. As shown in Fig. 1, system consists of a light source, a double fiber assembly, beam expanding and collimating lens, optical element, mechanical optical scanner and a photodetector. A plane mirror and reflection ruled or holographic gratings in Littrow arrangement (incident and diffracted angles are equal) are used in this experiment. Although other common arrangements such as Rowland, Grazing incidence, etc. can be used in grating spectrometers (Chen *et al*., 2004; Svanberg, 1991). A white lamp operating voltage of 15 V and current of 0.12 A is used here as a source light. The output reflected/diffracted light is converted into electric signal by a photodetector and the resulted voltage is measured by a digital multimeter interfaced to a PC. To control scanning operation of the optical drive system an interface driver is used and MATLAB program is written to control the scanning operation. The scanning operation is carried out in terms of the number of scan steps, which is converted into scanning angle by using a proper calibration line.

One important part of the spectral system is the required dive system for the scanning of dispersive grating. Common drive systems for linear and rotary positioning mechanisms use the leadscrew, ball screw and worm devices. Leadscrew and riding nut is a very popular technique for moving loads. Such a device has advantages like self-locking capability, low costs, ease of manufacture and a wide choice of materials. Ball screws drive is actually leadscrews with a train of ball bearing riding between the screw and nut in a recirculating track. The worm gear system is a technique of transforming rotary motion in one direction into rotary motion in another direction by meshing a screw with a gear.

A mechanical drive was introduced, which was based on a hinged sign bar drive that gives a true linear relationship even for large scanning angles. Design and operation of a conventional monochromator using such a scanning technique was given by Golnabi (1994). In the following study design and construction of a fine drive system for scanning optical elements is reported by Golnabi and Jafari (2008). A drive system similar to the one introduced by Golnabi and Jafari (2008), is used here for the scanning purpose and spectral analysis. A lead screw, a drive nut, sine bar legs and output shaft that can scan the optical holder mount. With a stepper motor coupled to the lead screw and interfaced to a PC, it is possible to control the scanning operation and two electro-mechanical micro-switches are used for stop function.

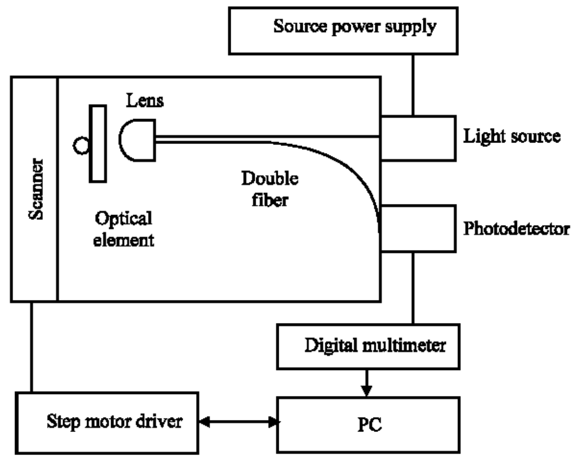

Fig. 1: Experimental set up for the operation of the system

When a 800 step/turn motor is utilized it is possible to have an angular resolution of about 0.5 mdegree for a dynamic range of about 23 degrees. The reproducibility of the results is about 0.22% for the scan angle and the hysteresis effect of the system is in the range of 1.71%. For a total scan of 51200 steps corresponding to an angle scan of about 23.3 degrees, the fitted line shows linearly with a correlation factor of 0.9995. With a good precision in system construction and alignment cares the overall nonlinearity is less than 1%. The optical element can be scanned both clockwise and counterclockwise. For the counter clockwise we present the scan angle as positive value and for clockwise scan we show with the negative sign in data analysis.

The overall mechanical resolution and operation of the mechanical drive system depends greatly on the resolution of the lead screw, the stepper motor and the drive module. Equally important to the system is the motor drive unit, which should be sufficiently smooth and precise to enable the full potential of the mechanical parts to be realized. Thus, a higher resolution stepper motor can be selected for the design, which offers a high constant torque over a wide speed range with low resonance and good magnetic damping to minimize the overshot. To control the motor driver, an electronic module was devised, which provides full control of the stepper motor stage, including its speed and traveling condition (Wildi, 2005; Keen *et al*., 1988; Domeki *et al*. , 1992). The control method developed in this experiment takes advantage of the MATLAB software functions (Hanselman and Littlefield, 2001).

RESULTS AND DISCUSSION

In the first test a plane mirror is used as a reflecting element and the reflected beam signal is monitored as a function of the step number. For a total scan steps of 51200 the scanned angle change is about 23.3°. The angular resolution of the present system obtained from previous study (Golnabi and Jafari, 2008) is about 0.0004° and the conversion step into angle is indicated by the calibration line in Fig. 2, which has a slope of 0.0004 degree/step. It must be noted that the angular resolution of the step motor is only 0.45 degree/step (800 steps/turn).

Figure 3 shows the reflection signal measurement of a plane mirror as a function of the scan step number. The reflecting mirror is at an initial angle of zero with respect to the fiber and optical axis. The output signal shows a variation of 2.2 V for a total scan step of about 40000. Even though it was possible to scan more steps (51200) but the limitation in scanning is because of the expanding lens and required distance that limited scan range to the shorter step numbers in most experiments. The source light for this experiment is a white lamp operating with a voltage of about 15 V and a supply current of 0.12 A. Care was taken to do all the experiments at the same supply voltage of the white lamp in order to be able to compare output signals.

In Fig. 4 the diffraction signal measurement of the ruled plane diffraction grating as a function of the scan angle is presented. The initial angle of the grating with respect to optical axis is -10° in clockwise direction (CW). As can be seen in Fig. 4, the output beam signal shows a decrease with angle up to 22° and from that point shows increase, which is indicative of the fact that the recorded beam at this angle is not the reflected beam at zero order.

In order to compare the results for the reflection and diffraction in Fig. 5 the results are shown together. To obtain data for this case two separate experiments are performed for the plane mirror and the grating at almost similar source and detection conditions. As can be seen the zero-order behavior of the diffraction grating as expected is similar to that of the plane mirror with the exception that has a better surface quality and provides higher reflection signal. However, at a scanning angle of about 20° grating shows the signal resulting from the diffracted light while such a signal is absent for the plane mirror.

As described it is possible to scan the optical element in both the clockwise and counter clockwise directions. To test this option in the further study with the same ruled grating, scan operations in both directions are performed and the results are discussed in this part. In

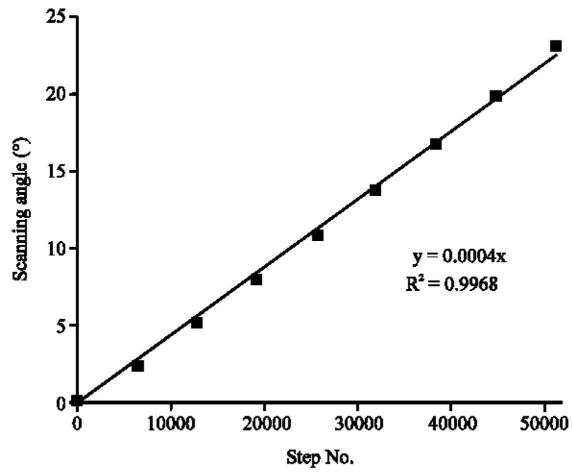

Fig . 2: Calibration line for converting step number into scan angle. The legends show the slope of the line and the correlation factor for the fitted line

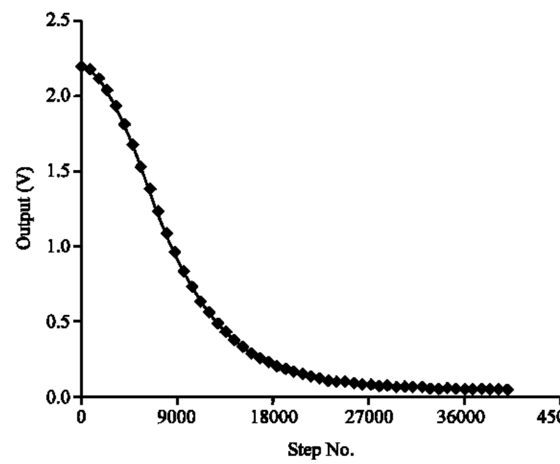

Fig. 3: Reflection measurement of a plane mirror as a function of the step number

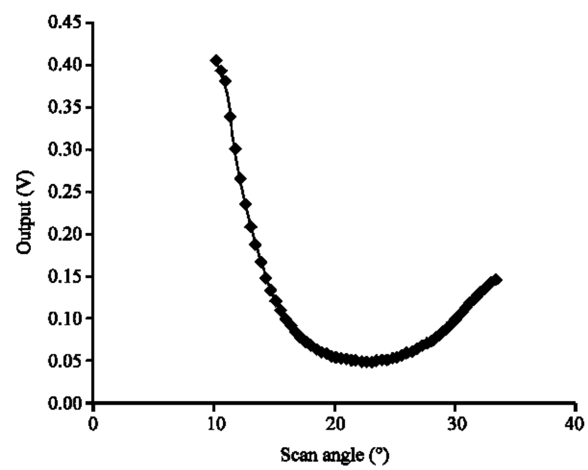

Fig. 4: Output signal of the ruled grating as a function of the scan angle for the initial angle of -10°

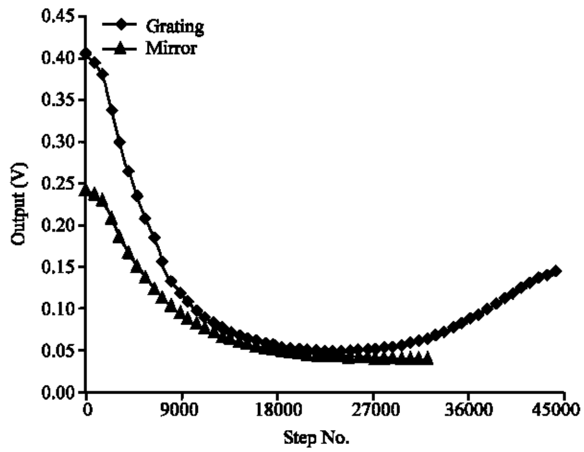

Fig. 5: Overlap of the plane mirror and grating reflected light signals

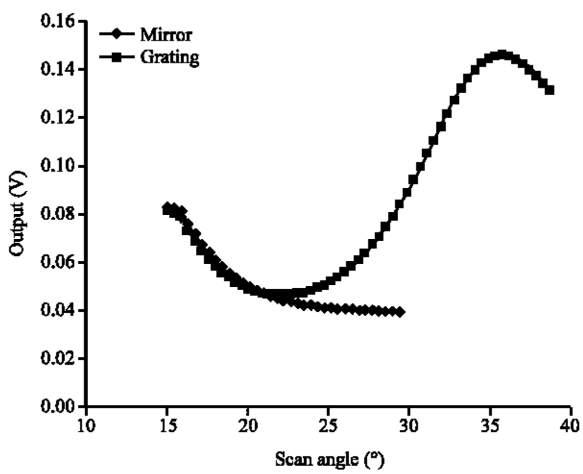

Fig. 6: Comparison of the outputs for the ruled grating and the plane mirror at initial angle of -15°

Fig. 6 the clockwise scan with the initial angle of -15° is shown for the white lamp source. As described before both the reflection and diffraction signal are present in the graph and the first part of the curve corresponds to the reflection and the second part shows the first order diffraction at an angle of about 35°.

In a similar way the output result for the counter clockwise scan operation is performed and the results are presented in Fig. 7. As can be seen the results are very similar to the CW operation with a little exception that a larger scan is possible for the plane mirror for the case of CCW as shown in Fig. 7. The main part the grating respond curve is almost similar to the CW case. Similar to the previous case the first order diffraction results at a scan angle of about 35 degree with the initial angle of 15°.

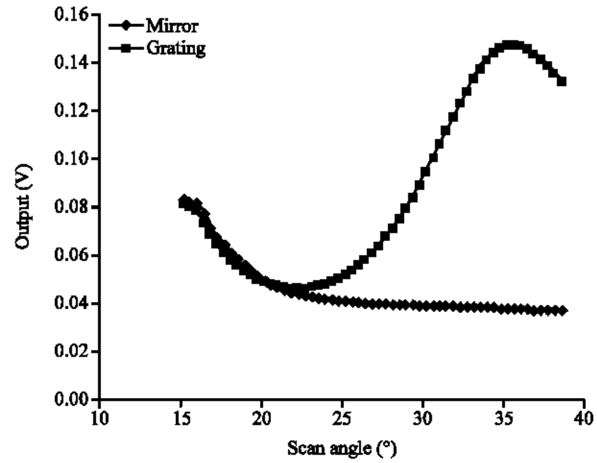

Fig. 7: Comparison of the outputs for the ruled grating and the plane mirror at initial angle of +15°

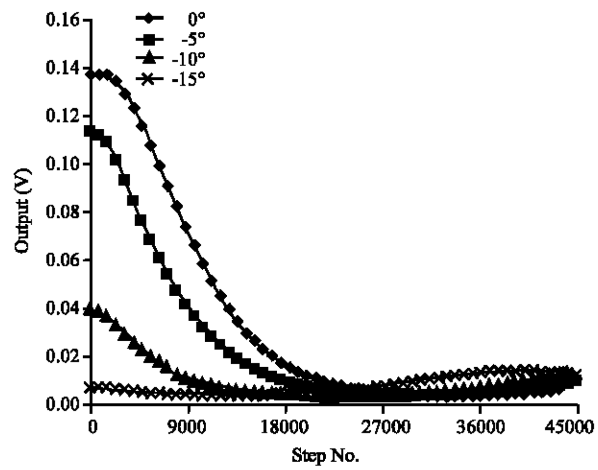

Fig. 8: Output signals of the ruled grating for different initial angles

Similar studies are performed for the initial angles of 0,-5,-10 and -15°, respectively and the results are shown in Fig. 8, as a function of scanning step number. As can be seen in Fig. 8, by increasing the initial angle the output beam signal drops from the range of 0 to 27000 steps (corresponding to scan angle value of about 10°) and from that angle the signal shows the increase for the first-order diffracted beam. The total scan corresponds to a scan angle of about 18°.

In order to resolve the zero- and the first-order beam signals, we patched the scan results for the initial angles of 0, -10 and -15°. Figure 9 shows part of the output signal for the zero and the first order diffraction patched from different scan data at different initial angles for the ruled grating. Comparing the results with the earlier figures it shows that the first half-peak shows the zero-order

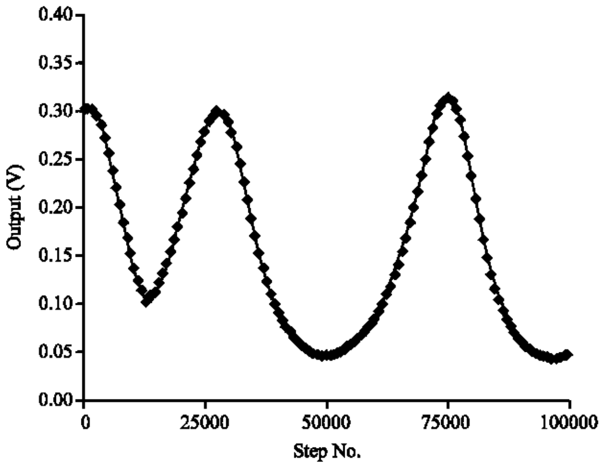

Fig. 9: Diffracted signals for the ruled grating at different initial angles

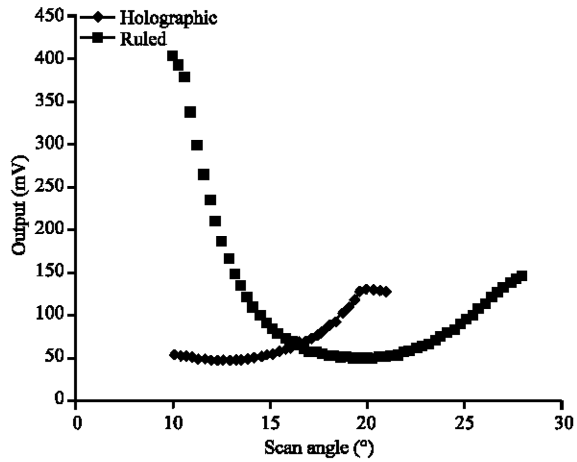

Fig. 11: Comparison of the output signals for the ruled and holographic gratings

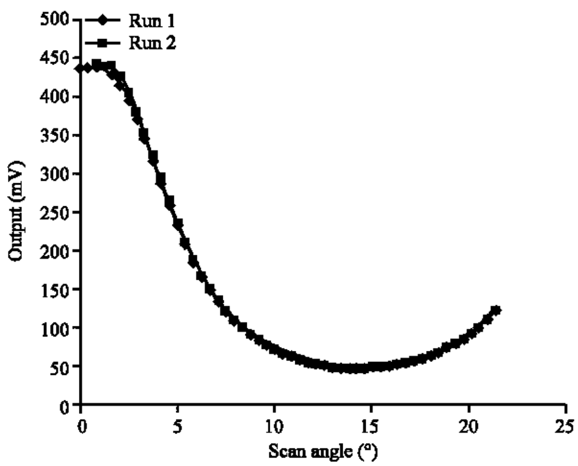

Fig. 10: Output signal of the holographic grating as a function of the scan angle

diffraction, second peak corresponds to the first order diffraction recorded at initial angle value of -10° and the third peak in Fig. 9 corresponds to the first-order diffraction signal at the initial angle value of about -15°. Since it is not possible to accomplish a large total number of scans in a single run, therefore, the results of different scans are patched together in a single graph to show the results.

Figure 10 shows the output signal measurement of the holographic grating as a function of the scan angle. As can be seen in Fig. 10, from zero to about 15° signal is resulted from the reflection signal and at this angle the signal is as a result of the diffraction in the first-order. Comparing the results for the holographic and ruled gratings it is noted that since the number of the grooves is lower for the holographic grating thus the first order diffraction angle is lower than that of the ruled grating. Another difference is the surface coating quality of the gratings in which for our case the zero-order output signal is higher for the ruled grating as can be seen in Fig. 8 and Fig. 10.

Reproducibility of the results for the designed system is also shown in Fig. 10 for the holographic grating. The reproducibility of the results in terms of the scanning angle is presented for two consecutive runs. As can be seen in Fig.10, two curves are nicely overlapped where the minimum difference is about zero and the maximum deviation is about 10.75 mV. The average value for the signal difference is about 5.37 mV (1.21 %), which is a very good reproducibility. A similar reproducibility in results is obtained with the ruled grating.

In Fig. 11a comparison of the output beam signals for the ruled and holographic gratings are presented. As indicated in Fig. 11, the initial angle for both gratings are equal to -10° and other conditions are the same. The groove number for the ruled grating is 1370 groove/mm (first-order diffraction angle 20° at 500 nm) and for the holographic grating is 1200 groove/mm (first-order diffraction angle 17.45° at 500 nm) with a blaze angle of 21° at 600 nm wavelength. Unfortunately we do not have information about the blaze angle for the ruled grating.

However, considering the line numbers for the two dispersive elements the first order diffraction angle theoretically is larger for the ruled grating in comparison with the holographic one calculated for the average wavelength of 500 nm (middle of the visible range). As can be seen in Fig. 11, the first order diffraction occurs at a larger scanning angle for ruled grating, which verifies the theoretical estimation for diffraction gratings.

In summary, design and operation of an opto-mechanical system using a double fiber optical design was reported for spectral analysis. The first-order diffraction of the white light source is obtained by using the diffraction grating. By comparing the output signals of the plane mirror and plane grating it is concluded that the output signal is related to the first-order diffraction rather than zero order, which corresponds with that of the plane mirror. With a simple modification of the drive part, it is possible to extend the scanning range of the mechanical scanner and as a result system. With such a system it is possible to record higher order diffraction signals as well as the zero- and first-order results presented here.

Based on present theoretical and experimental results the reported scanning system provides high resolution and high linearity, even for larger scanning angles if the proper care is taken into consideration in its construction. By use of the half step excitation drive option it is possible to improve the mechanical resolution by a factor of 2. By implementing a high quality grating (6000 groove/mm) it is possible to improve the overall resolving power of the device considerably. The sensitivity of the system can be improved by improving the light source, photodetector, double fibers and the fiber couplings to source and detector. Beside the conventional equipments such as spectrometers the reported unconventional system can help to develop new wavelength selective devices for specific application with higher efficiencies in a more compact way.

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