Design of a control system for interferometric fringe stabilization system with remote access

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ABSTRACT

Stability in a fringe pattern is a necessary condition in interferometric processes, such as holography, and not always is enough the use of passive stabilization systems, like holographic tables, in particular, when perturbations are caused by thermal or acoustic variations. For these cases, active systems are required. In this work it is presented the implementation of a control system for interferometric fringes stabilization. The interferometric arrangement characteristics are also discussed, which permits to act independently over each of the interferometer's arms by means of two piezoelectric actuators that change the length of the optical path of light that goes through, in order to perturb the system and simultaneously compensate this perturbation in real time. It is also shown that the proposed system allows evaluating the control system's performance subjected to diverse perturbations, and it is shown how remote access was given to the implemented platform.

Keywords: Proportional control, fringe stabilization, interferometric fringes, phase compensation, Mach-Zehnder, LabVIEW™, RENATA.

1. INTRODUCTION

There exists a wide spectrum of experiments and applications in optics, and optical instrumentation, based on the interference among two or more coherent light waves, which requires stability control. One of them is holography.

Holography is based on the recording of an interference fringes pattern, produced by laser light. These fringes, usually, have high spatial frequencies, of typically thousands of fringes per millimeter, and that is the reason why some special stability conditions are required in order to avoid the fringes' movement and the consequent blur of them in the records. Ordinarily, in a holographic recording, a movement of around 0.5 microns is enough to produce data loss, so the control for the stabilization system, if used, must be efficient and reliable.

Among other causes of the instability of interference fringes, one can find mechanical variations of the optical components, external perturbations transmitted to the experimental arrangement, thermal variations in the path of laser beams which are interfering, and instability of laser itself. One way to counteract these effects is decreasing the recording times (increasing potency of the lasers used), and another way to do so is the use of special experimental configurations, not always feasible, or the implementation of fringe stabilization systems.

The stabilization systems for interference fringes can be classified into two groups: passive and active. Among the passive ones there are diverse support structures and tables for the optical devices used, which shall be extremely stable and isolated from external vibrations[1,2]. Specifically, isolated tables are used for optical experimentation, metrology and some other applications which require high stability. Usually, these tables, known as holographic tables or optical tables, are massive (more than 100 kg), which allows them to absorb efficiently vibrations transmitted from the ground or the table's supports. Some of them are characterized by having pneumatic systems to absorb vibrations on their supports, and a minimum contact area between them and the top of the table. This kind of stabilization systems are usually expensive, and present the disadvantage of being non portable, making in general impossible to work outside the laboratory. On the other hand, one have to keep in sight that there are some perturbations which affect an interferometric fringe system that cannot be eliminated by a passive system, such as local variations of temperature or acoustic vibrations spreading in the air, and sometimes additional stabilization systems are needed, specifically, those known as active systems.

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Active stabilization systems are useful to keep a fringe pattern stabilized, making in real time needed adjustments to compensate the phase differences caused by external perturbations, belonging to a mechanical or thermal kind, or to any other nature. There are currently available commercial fringe stabilization systems[3]. In essence, operation of these systems is based on the possibility of readjust, in real time, any parameter from the experimental scheme, for instance the position of a mirror or any other element, according to variations produced in the interferometric fringe pattern of interest. For that, a feedback signal in the output pattern is required; signals being detected by appropriate sensors are processed by a computer or embedded control system to produce the signal that will serve to drive, usually by electro-mechanical or optoelectronic actuators, the adjustments needed to maintain the pattern stable.

2. INTERFEROMETER INSTRUMENTATION

The device implemented is a Mach-Zehnder interferometer. The interference pattern is observed by means of a CCD LC100 camera produced by Thorlabs, which has a linear sensor of 2048 pixels and connects to the computer by using the USB interface. Using the LabVIEW™ software, data are acquired, and in real time some perturbations are introduced into the system via a PAS005 piezoelectric actuator made by Thorlabs, connected to one of the interferometer's arms, and compensation in real time is made via another identical actuator located on the other interferometer's arm. Both actuators are connected to the MDT693A driver, manufactured by Thorlabs, which receives data from the computer via RS232 for perturbation and via a National Instruments NI-USB6008 compensation card. This scheme is presented on Figure 1.

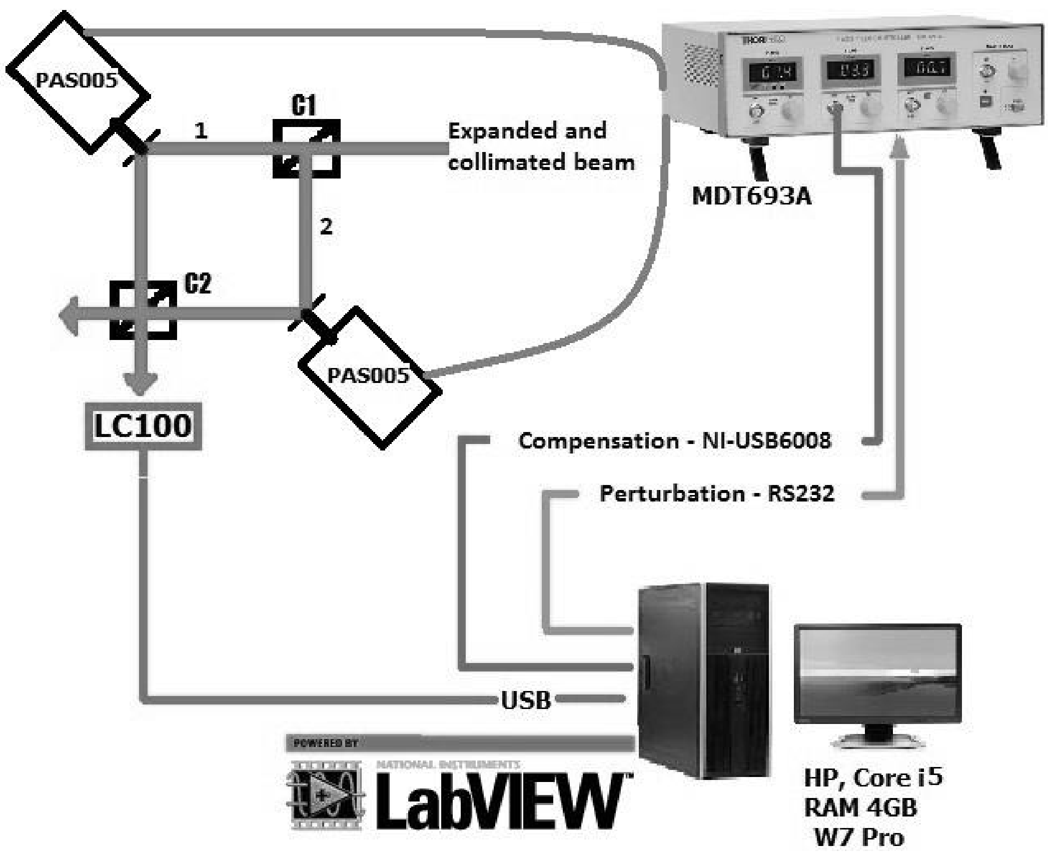

Figure 1. Instrumentation of the system: A linear CCD LC100 camera from Thorlabs is used for sensing, and actuation over the system is achieved by means of two PAS005 actuators and a MDT693A driver from Thorlabs.

The main objective of the control system designed is to keep the position of an interference fringe pattern in a fixed position, which will be called Setpoint (SP). Due to the interference pattern is composed by a series of maxima and minima of intensity, we implemented the algorithm to find and follow the position of a minimum of the pattern chosen. The minimum chosen is taken as a reference to locate the fringe pattern position in the successive, and that is why it will be called Reference minimum. The error signal (e) is the subtraction between SP and the Reference minimum, which will be called processed variable (PV). SP is taken as the position of this reference minimum when the system begins to “observe” the pattern, this is, SP is PV at the first iteration of the computational cycle.

Since sensing is made digitally, using a linear CCD camera, positions for SP and PV, as well as the error value, are given in pixels, so that the controller has the input in pixels and the output in volts. Controller must be understood as the LabVIEW® algorithm which receives the error signal in pixels and sends to the compensation actuator a signal in volts. This controller output (in volts) is the input for the piezoelectric actuator 1, which modifies the length of the optical path of light in the respective interferometer's arm, through the movement of a mirror. The signal sent to the actuator 1 is what forces the selected minimum of the intensity pattern to come back to the SP position when error is different from zero. By using a second actuator, also controlled via the computer, we can modify the optical path's length of the other arm of the interferometer. The signal sent to the second actuator causes a perturbation into the interferometer, but can also become null if desired. This signal is used to evaluate the system's capacity to control perturbations of different profiles, amplitudes and frequencies. Some profiles, such as cosine, square, triangular, ramp or chirp, can be chosen. It is worthy to mention that computer is a fundamental part on this system, because camera can monitor in real time the interference pattern, and by using actuators 1 and 2, via the computer we can act over the system in order to perform both control and perturbation, respectively.

The interferometer, configured in this way, permits to introduce a known perturbation in one of its arms, chosen from the computer, while in the other arm one can actuate with a signal calculated by the control system, to compensate changes in the fringes´ positions. Then, the mirrors E3 and E4 can be moved in a perpendicular direction from their surface, to properly change the optical path's length in the respective arms, through the actuators 1 and 2. In this way, perturbation can be introduced into the optical system, and be compensated online via the control cycle.

3. CONTROL SYSTEM

To design the control system, the first step was to identify the system. Figure 2 shows the conception of the system. Its input is the voltage assigned to the compensating actuator, and its output is the position of the interference pattern detected by CCD camera.

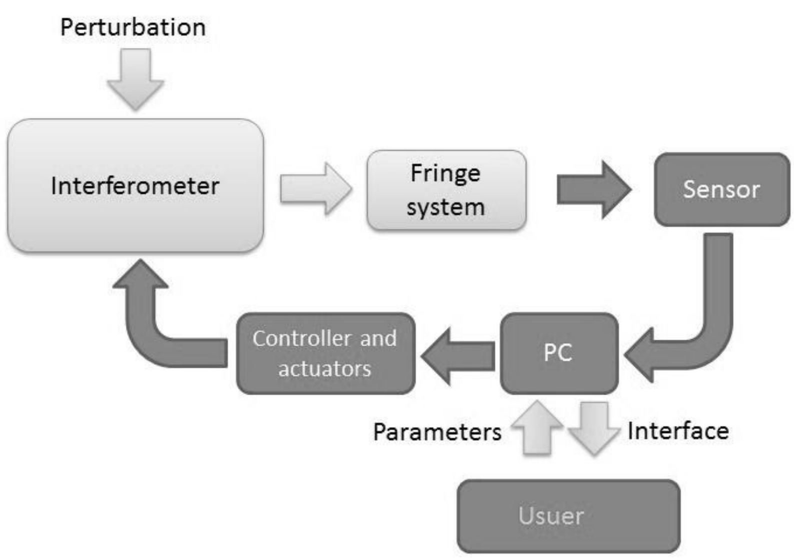

Figure 2. Blocks diagram for the controlling system.

In order to conduct an appropriate identification, a Gaussian white noise stimuli signal was introduced, obtaining a temporal exact correspondence between variations on input and output signals, as shown on Figure 3. This occurs because the actuator's response lapse forces PV to refresh in a lapse minor than the sampling period.

In Figure 3 it is apparent that any change on the input signal for actuator's voltage produces a change (proportional to the voltage's change) immediately. It can also be observed that there is no over-impulse and no establishment time; this means, since this is a system in discrete time, the fact that the same interaction in which input changes the output also does so, and always in the same proportion, which in turns means that there is no delay linked to the system's response. Of course, this behavior is non typical, because in a conventional system, when an input is modified, it in general take a finite time to take its output signal to the final value, the established time, and usually the signal path towards its final value goes over by a little extent, and then comes back to the stationary value, presenting what is known as over-impulse.

A deeper exam on the dynamic characteristics of the system's components explains, in an exact way, the reason for this behavior. We should now remember that the sampling frequency the camera has observing the interference pattern is around 300 Hz; this means that for each capture cycle, camera will take a lapse of around 0.003 seconds.

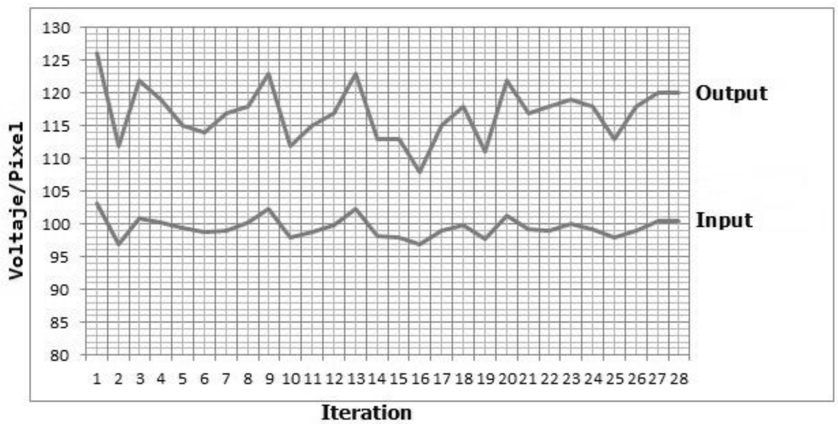

Figure 3. Stimuli data and system response for an input signal of gaussian white noise filtrated.

On the other hand, the piezoelectric actuator's slewrate is 16.7 V/ms, and given that voltage changes to which the actuator is submitted are 1V as maximum, it follows that in order to reach its final position the actuator takes a lapse of:

$$\frac{1}{16.7}ms = 0.06ms = 60\mu s \tag{1}$$

This lapse is lesser than the lapse in which camera is taking recordings. So then, although effectively actuator has to have a dynamic, there is no way of perceiving it with the available devices, because it would require a camera with a capacity of taking recordings with periods inferior to $6\mu s$, which would be equivalent to around 166666 FPS. Then, when the system receives an input, output would be instantly (to practical effects) that same input multiplied by a constant. This means that an adequate way to deal with the problem of fringe stabilization, with current instrumentation, is made by a proportional controller which constant is related to wave length used and with the value that has to be assigned to the actuator input in order to produce a gap to compensate this error.

3.1 Proportional controller

A displacement Δx on the actuator, in any of the arms of the Mach-Zehnder device, produces a change in the optical path's length of light that goes over in the respective arm, given by $\sqrt{2}\Delta x$. Then, in order to move the interference pattern a complete spatial period, the actuator has to move $\lambda/\sqrt{2} = 0.6328\mu m/\sqrt{2} = 0.4475\mu m$. The used actuator goes over $20\mu m$ when voltage changes from 0V to 75V. This means that, to move the pattern exactly one spatial period, voltage must change in:

$$0.4475\mu m * \frac{75V}{20\mu m} = 1.68V \tag{2}$$

It was found experimentally that the exact value for this system is 1.87V, which differs from the value given by the manufacturer ($75\,V/20\,\mu m$). We conclude that the value given by the manufacturer is quite approximate if calculated from the complete travel of the actuator, but this is not the appropriate value for our experiments, because the magnitude of displacements required for our system is very small in comparison with the maximum displacement of the actuator. This is why we determined experimentally the gaining value (approximately) linear in the range of interest, and based in this value we obtained the exact value of 1.87 volts to move the pattern one period of fringes.

Having that in mind, a constant was proposed for the proportional controller, which value must adjust in function of the fringe period, given by the equation:

$$K_p = \frac{1.87}{periododelasfranjas} \tag{3}$$

A higher constant will produce rough movements, and a lower constant would be inefficient because the controller would require various iterations in order to conduct the compensation on a given gap.

4. PERFORMANCE EVALUATION

In order to evaluate the control system to compensate external perturbations, a sinusoidal horizontal movement will be introduced intentionally into the mirror of one of the interferometer's arms, via the perturbing actuator. When the mirror moves in an oscillatory way, the interference pattern moves also with the same frequency and with amplitude proportional to that amplitude in volts of the oscillation introduced into the actuator. This oscillatory movement has the option to adjust, from the user interface, the frequency and the amplitude of the oscillation; in this way, performance of the controlling system can be analyzed, as well as its capacity to compensate oscillations of the pattern without any a priori knowledge about its characteristics.

A typical result for the actuator's behavior is presented in Figure 4, in which is shown the pattern's position (PV) in function of time, when the system is perturbed with a sinusoidal signal. Referring to this graphic, compensation does not act until a time of 0.96s, but the perturbing actuator makes the pattern oscillate around the 16 pixel with an error of about ± 4 or 5 pixels. When the controller is turned on, despite the perturbing signal keeps on acting over the system, PV oscillates around the setpoint with an error of no more than ±1 pixels (±14 μm).

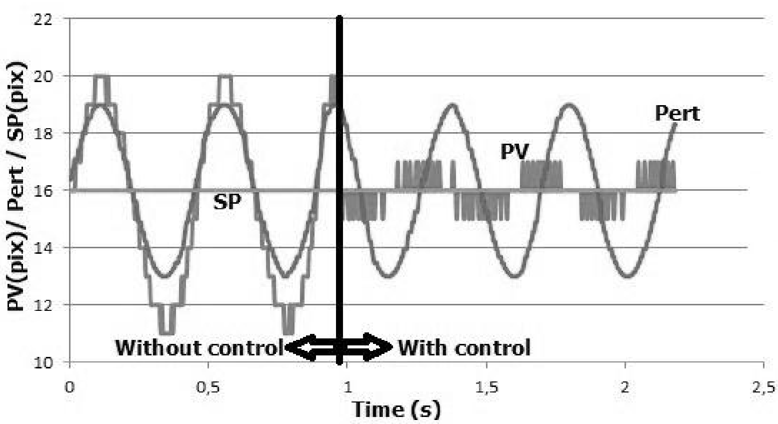

Figure 4. Position of the pattern (PV) around the setpoint (SP) in front of a perturbation, without control (from 0 to 0.96 s) and controlled (from 0.96 and onwards) to a maximum PV with control of ±1 pixel.

Complementarily, to determine the control system´s capacity to compensate phase differences, error histograms can be visualized in the user interface. In Figure 5 are shown two typical histograms, to the left when the controller is not active, and to the right when the controller is active. One can appreciate that, for this particular case, by means of the control system one can reduce the pattern's oscillation around SP at ±1 pixel.

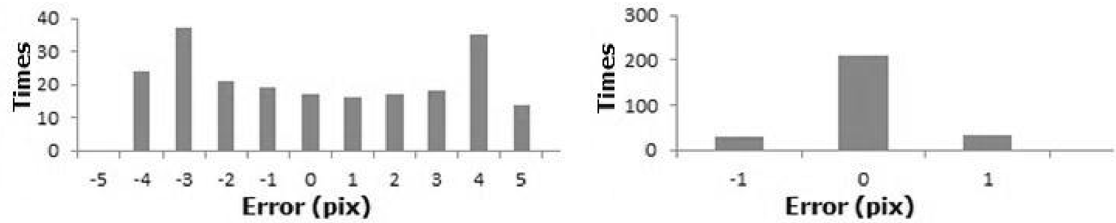

Figure 5: Histograms from the error signal without control (left) and controlled (right) to a maximum controlled PV of ±1 pixel.

The histograms of error signal without control (Figure 5) indicate that the fringe system remains much longer near the oscillation extremes, and in consequence more measures are taken near these extremes, and the speed with which the pattern displaces (for sinusoidal perturbations) reduces near the valleys and peaks of oscillation. On the other hand, histograms of error signal, when controlled (Figure 5), put in evidence that, once the control system began its actuation, fringes remain much longer near the SP, corresponding with a larger number of measures in that position, related to measures taken out of the SP.

As mentioned before, it is necessary to quantify the lapse in which PV signal remains on the SP. To achieve that, in every instant, the control system calculates the error variance, which indicates how wide the error histogram is, as shown in Figure 5.

Finally, to know the performance of the control system, an algorithm has been implemented to measure the interference pattern visibility which would be observed if there were used integration times longer than the characteristic periods of oscillations constitutive of perturbations introduced into the interferometric system. This visibility value, calculated in this way, constitutes a measure for the contrast of a recording, conducted via a camera or any other linear recording method, in condition of using an exposure time higher than the temporal period characteristic of perturbations introduced into the interferometer. To calculate visibility, are used the intensity values measured at the setpoint position (the reference minimum for the control system) and at the position corresponding to one of the consecutive maxima for this minimum, at the moment when that setpoint was established. Values are measured in these two places during 240 capture iterations, and then an average of intensity on the respective pixels is taken. The calculation of visibility is conducted using these intensity averages, as follows:

$$\vartheta = \frac{\acute{I}_{máx}+\acute{I}_{mín}}{\acute{I}_{máx}-\acute{I}_{mín}} \tag{4}$$

where $\acute{I}_{max}$ and $\acute{I}_{min}$ represent the average intensity values, measured (by default, but adjustable to other values) in the 240 consecutive cycles of camera capture, in the positions of the minimum and one of the consecutive maxima chosen. 240 cycles were taken by default, because sampling frequency is of about 240 Hz, which is much superior to the characteristic frequencies of perturbations introduced into the system.

It was observed that the pattern visibility presents a very regular behavior, diminishing monotonously in the extent in which frequency increases, being more dramatic this decrease when the amplitude of perturbation increases. This is due to the speed at which the pattern displaces is proportional to the product of frequency and oscillation amplitude.

5. REMOTE ACCESS

Configuring the computer that controls the fringe stabilization system as a server, and using the labVIEW™ "Web Publishing Tool", we created a web page in which the platform is accessible, which was included into the platform created at Universidad EAFIT (Colombia) to remotely access to different laboratory equipment from the National

Academic Advanced Technology Network (RENATA, by its initials in Spanish) (weblab.dis.eafit.edu.co/). In this web page, a remote user can ask for an appointment to access the equipment and conduct tests in the control area using the fringe stabilization system implemented.

6. CONCLUSIONS

An interferometric fringe stabilization active system was designed and implemented, which can be used to improve visibility of an interferometric recording. It was evaluated the system's capacity to compensate the phase differences produced by means of external perturbations characterized for an oscillation of the fringe pattern, with known profiles, frequencies and amplitudes.

A virtual instrument was designed and implemented in labVIEW™, which receives via USB the interference pattern data taken by a linear camera. The algorithm sends a signal of perturbation to an actuator in the interferometer via RS232, then detects the position of each one of the pattern's maxima and minima, evaluates the error signal, and finally calculates and sends the control signal to an actuator through a data acquisition card connected to the computer via USB.

Due to the high response speed (Slewrate) of the implemented actuator (PAS005 from Thorlabs), the system was identified as a system without dynamic, this is, the control signals sent to the system from the controller take less than an iteration to establish the new value of the processed variable and, therefore, make the system transference function to be a constant given by the wave length of light used, the spatial period of fringes and the actuator's gaining.

A proportional controller was implemented, which constant is the inverse of the system's transference function. Using this constant, the designed controller is able to take the interference pattern to the setpoint position in any time inferior to a sampling period given by the camera.

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