Chapter 2

In-situ Optical Control and Stabilization of the Curing Process of POLICRYPS Gratings

Introduction

Since the early invention of holography in 1947 by Gabor[12], it was clear that the high degree of sensitivity of this technique required realization of a series of accurate experimental conditions. Utilization of lasers as sources of monochromatic radiation solved one of the main problems and since that time on, several drawbacks have been rapidly overcome. Nowadays the application of holography ranges from simple holographic imaging to refined investigation tools like vibrational analysis, non-destructive testing, airflow visualization and even new concepts for realization of data storage media. In the last 15 years, a new important application arose in the realization of holographically obtained systems: Since the pioneering work of Sutherland et al[8], it has been observed that use of the light pattern provided by two (or more) interfering beams can be successfully employed to obtain holographically sculptured, sharp morphologies in photosensitive materials.

The quality of obtained structures is underlined by a large number of scientific papers confirming the effectiveness of the technique; this has been used for the realization of different physical systems like switchable diffraction gratings[8], photonic crystals[13] and organic lasing systems[14,15]. However, when a particular experimental accuracy is required, it turns out that some drawbacks still exist. We have shown[16] that, if the stability of the experimental setup is not carefully controlled, the process of writing diffraction gratings in liquid crystalline composite materials by utilizing a UV interference pattern (usually referred to as “curing process”) can be drastically affected by setup vibrations, with a noticeable influence on the resulting morphology of fabricated samples. The present chapter, reports on a novel technique which enables monitoring and control of

the curing process of holographic gratings; use of this technique prevents the occurrence of above mentioned morphology flaws, since a feedback system is included which efficiently suppresses incidental setup instabilities.

2.1 Setup stability testing

The stability of the experimental setup is a key element when considering realization of holographic diffraction gratings by UV curing techniques. A measurement of the phase shift existing between the curing interference pattern and the grating being cured gives a precise idea of the system stability. The hint of performing this measurement has been already exploited[16] we designed an optical interferometer (sketched in Fig. 2.1) which included an *in situ* control system and enabled a continuous monitoring of the overall stability of the setup.

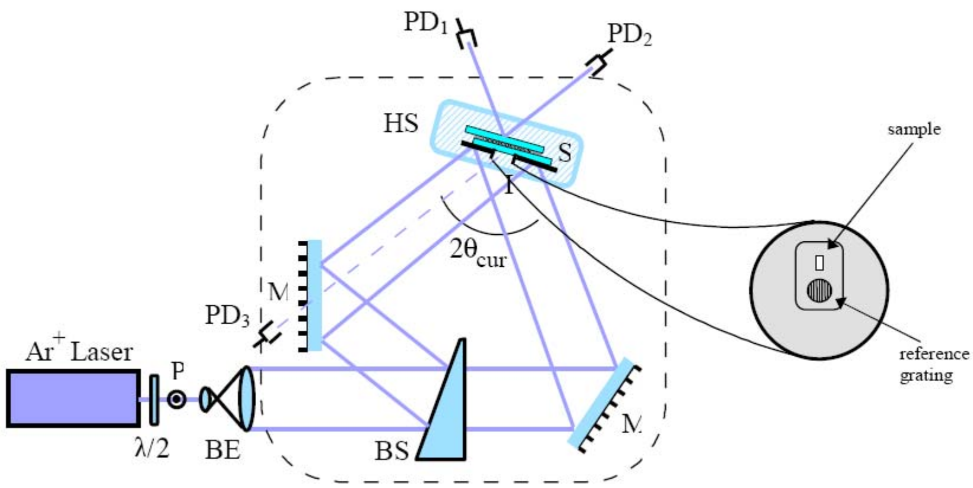

Figure 2.1: Optical setup for UV curing of POLICRYPS gratings with stability check. **P**, polarizer; **λ/2**, half-wave plate; **BE**, beam expander; BS, beam splitter; $\mathbf{2\theta_{cur}}$, total curing angle; **M,** mirrors; **HS**, hot stage; **I**, tuneable aperture; **S**, sample; $\mathbf{PD_1}$, first beam photo-detector; $\mathbf{PD_2}$, second beam photo-detector; $\mathbf{PD_3}$, diffracted/reflected beam photo-detector. In the insertion it is shown the reference grating (put immediately below the sample area) which enables the stability check.

This is the standard one already used to cure POLICRYPS gratings[9-11], in which a modification has been introduced for stability control purposes: A commercial, metal-coated, reflective diffraction grating (Edmund Optics) has been mounted on the same steel disk which holds the sample. The aperture of this grating (4 mm circle, insertion in Fig. 2.1) is vertically separated by a 3 mm distance from the sample aperture; thus, the peripheral part of the impinging 15 mm broad spot is reflected and contemporarily diffracted by this reference grating.

The angle of intersection of the two interfering beams has been precisely settled to make the reflected part of one beam spatially coincident with the diffracted part of the second one; that is, these two radiations are wave-coupled by the reference grating. The obtained diffracted/reflected wave, after spatial separation from the incident one (achieved by a slight misalignment of the reference grating in the vertical direction) is detected by an additional photodiode PD_3 placed above one of the two mirrors of the interferometer. The signal voltage given by this photodiode is:

$$V_{PD} \propto I_{PD3} = I_{d2} + I_{r1} + 2\sqrt{I_{d2} I_{r1}} \sin \varphi_{\exp} \qquad (1)$$

Where I_{PD3} indicates the intensity which impinges on the photodiode, $I_{r1,d2}$ are the intensities of the reflected part of the first beam and the diffracted part of the second one respectively, while φ_{exp} is the phase shift of the reference (and cured) grating with respect to the curing interference pattern. By using expression (1), we were able to monitor the temporal variations of φ_{exp}:

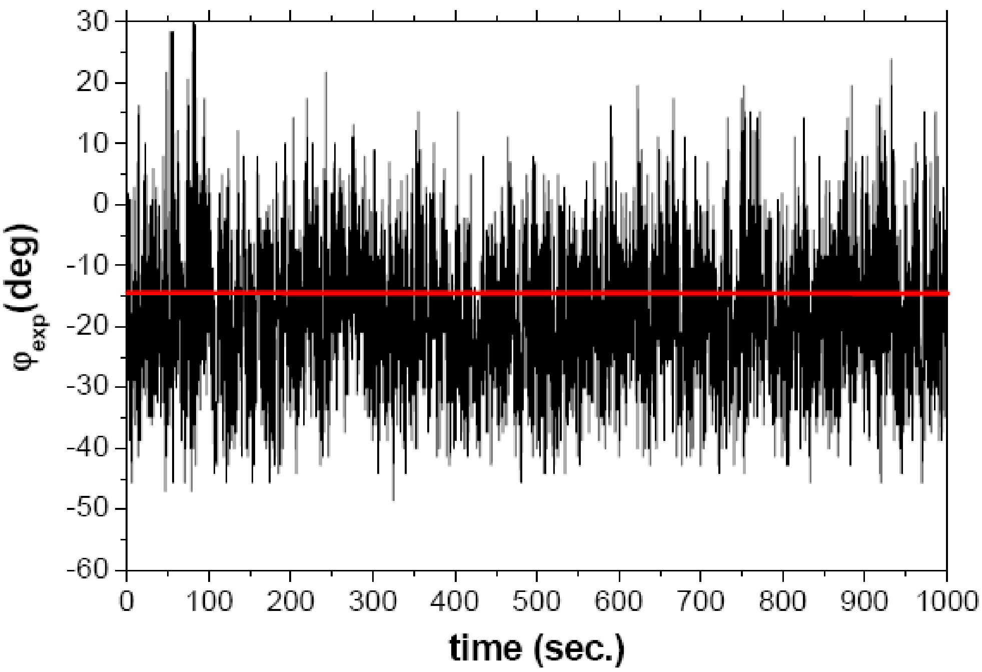

Figure 2.2: Preliminary check of the grating stability. Typical phase deviations of the interference pattern with respect to the test grating during the first 1000 sec. are reported.

We have found they sometimes exceeded ±30° during about 1000 sec. (Fig.2.2), notwithstanding an anti-vibration table with an auto-leveling pneumatic system (standard for interferometric experiments) has been used. These variations correspond to a stochastic trembling of the curing pattern; hence, during the curing, the sample undergoes a sort of 'blur' effect which drastically affects the final morphology of the obtained structure.

2.2 Piezo feature analysis

There are several ways to start solving the illustrated problem. The first one, which has been already adopted[16], consists in removing any possible "transmission of noise"; this has been obtained by adopting reinforced posts and mounts and placing the interferometric part of the setup (indicated by the dashed rectangle in Fig. 2.1) on a thick steel plate. Moreover, to avoid temperature variations and/or acoustic noise, this part has been covered by a hermetic box made of sound absorbing and thermo isolating material. After adoption of these cares, phase shift deviations were limited to values of approximately ± 4-5°. Although this solution has enabled the realization of interesting experiments on the two-wave coupling which takes place during the curing process, there is still an evident limitation in setup performances, since instabilities have been only reduced but not satisfactory suppressed. In fact, residual vibrations evidentiated by the above mentioned range of φ_{exp} oscillations (±4-5°) still affect the quality of the morphology of the cured grating. In particular, they contribute to the formation of intermediate zones between polymer slices and liquid crystal films[9], which increase the response time to an applied external voltage, thus reducing the interest towards possible uses of these devices for electro-optical applications.

On the other hand, the simple solution of curing POLICRYPS structures by utilizing a commercial transmission grating put after a single (broadened and uniform) laser beam cannot be adopted. Indeed, the possibility of choosing in any moment the spatial period of fabricated POLICRYPS gratings (by appropriately setting the angle between the two interfering curing beams) is an experimental feature which is of fundamental importance for most of the characterizations of sample properties. An active way of preventing vibrations and instabilities of the interferometric setup has been therefore explored. Some commercially available fringe locker systems[17,18] need introduction of a second laser beam to produce a reference signal, which is obtained by inserting additional beam splitters in the setup. This would result extremely difficult to be done in our experiment . Furthemore, in order to detect the time evolution of the diffraction efficiency during the curing process, if would be necessary to introduce a further laser beam and, again, additional optical elements. In this way, the apparatus would become extremely cumbersome. Other commercial systems[19,20] make use of a fringe detector and a PZT mirror and exploit the idea of coupling part of the impinging beams. The device is particularly suitable for reflection gratings, but results of difficult use for transmission ones. Furthermore, in the case of POLICRYPS, the presence of a hot stage introduces additional difficulties to the possibility of coupling part of the curing beams. Some scientific papers on the argument deal with a technique utilizing an additional lock-in amplifier, (and resulting therefore complicated and expensive)[21] or acusto-optic and phase modulators[22]. In this case, the setup would become extremely cumbersome and impossible to be used for POLICRYPS realization, especially when a very short fringe periodicity is requested. The solution was suggested, instead, by an attempt realized on a different experimental setup[23] and consists in the employment of a piezo-driven mirror in one of the two branches of the curing interferometer. By controlling the position of this mirror by means of a suitable feedback algorithm, it is possible to neutralize any source of noise in real time, thus avoiding stochastic oscillations of the phase shift.

In order to implement the system, we started with a characterization of the features of the piezo mirror itself, consisting in a 3-axis piezo system (KC1PZ-MDT693 series by Thorlabs). By increasing the voltage *VPS* applied to the Piezo, we were able to modify the optical path of one of the two arms of the interferometer, thus obtaining an appreciable variation of the signal *VPD* given by the photodiode *PD3*. A typical result is shown in Fig. 2.3:

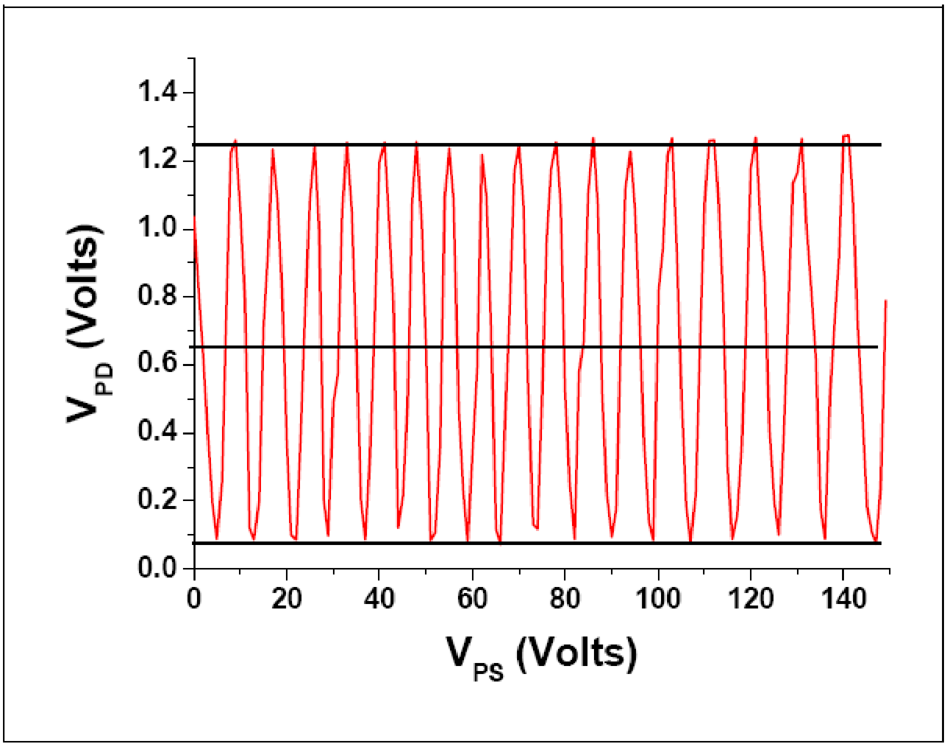

Figure 2.3:. The reference interference signal *VPD* is reported as a function of the piezo-mirror driving voltage *VPS*.

We have varied the voltage *VPS* from 0 to 150 V (which represents the maximum driving voltage of the piezo) applying contemporarily the same voltage to the 3 axis of the system, in order to ensure a translation of the mirror in a direction parallel to the optical path. In the figure, a sine-like behavior can be recognized which represents qualitatively the plot of expression (1). A fitting analysis can be performed by taking into account a dependence of the phase shift φ_{exp} on the voltage *VPS* applied to the piezo; equation (1) can be rewritten as:

$$V_{PD} = A + B\sin\left(C + DV_{PS} + EV_{PS}^2 + FV_{PS}^3\right) \quad (2)$$

where $A \propto I_{d2} + I_{r1}$, $B \propto 2\sqrt{I_{d2} I_{r1}}$, and the phase shift has been substituted with its 3rd order approximation power series development $\varphi_{th} = C + DV_{PS} + EV_{PS}^2 + FV_{PS}^3$. Parameters, *A* and *B* can be easily measured while *C*, *D*, *E*, *F* are obtained by a best fit procedure. For the particular case reported in Fig. 2.3, from measurements of I_{r1} and I_{d2} we have obtained respectively *A* = 0.67 V and *B* = 0.58 V, while results of the best fit procedure have given *C* = 0.93, *D* = 0.74 V^{-1}, *E* = 0.0181 V^{-2}, *F* = 0.00001 V^{-3}. It is worth noting that the actual value of these parameters strongly depends on the particular experimental conditions; hence a new experiment of the same kind would give different parameter values. In Fig. 2.4, measured and fitting curves of the dependence of *VPD* on the voltage *VPS* are reported.

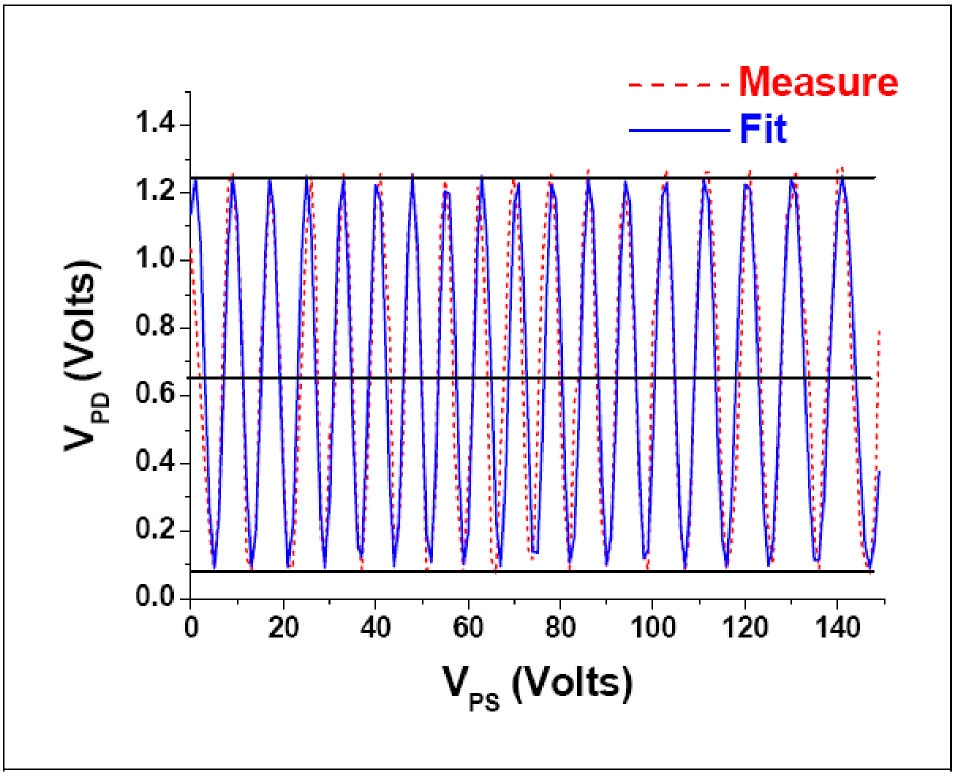

Figure 2.4: Comparison between the experimental dependence of the interference signal *VPD* on the piezo-mirror driving voltage *VPS* and fit of the same dependence performed by utilizing eq. (2) (dots).

A qualitative agreement is evident and in order to make a quantitative comparison, we have calculated the residuals, defined by:

$$\varphi_{res} = \varphi_{exp} - \varphi_{th} \quad (3)$$

where φ_{exp} can be deduced from (1) as $\varphi_{exp} = \arcsin\left(\frac{V_{PD} - A}{B}\right)$. The plot of residuals φ_{res} versus *VPS* is reported in Fig. 2.5, which gives an important information about the optimal region of operation of the piezo system:

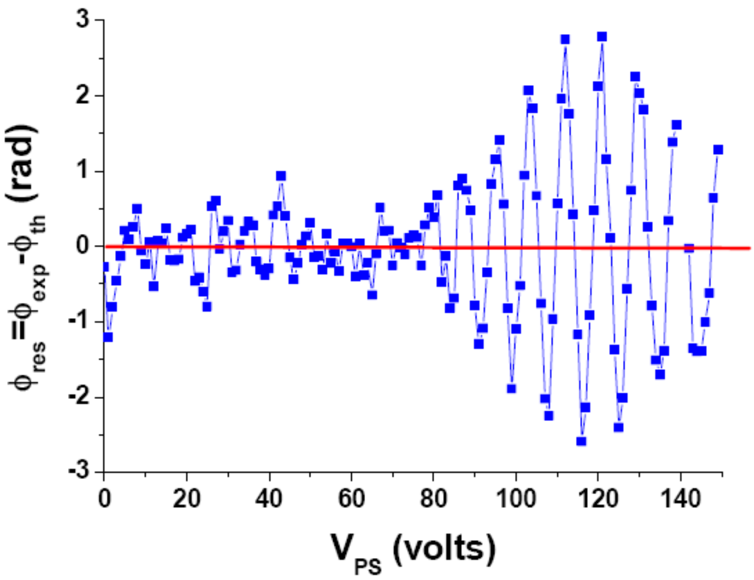

Figure 2.5: The residual phase shift φ_{res} is reported as a function of the piezo-mirror driving voltage *VPS*.

It can be observed that the agreement between experimental and approximate values of the phase shift remains quite good within a voltage of about 80 V. This is confirmed by the further observation that, for low values of *VPS*, the non-linear part $\varphi_{nl} = EV_{PS}^2 + FV_{PS}^3$ in the Taylor development of φ_{lh} versus *VPS* is almost negligible.

When repeating the experiment, the behavior depicted in Fig. 2.5 has been always confirmed. This experiment represents therefore a useful probe to establish the optimal range of operation of the piezo system.

2.3 Feedback algorithm

We proceeded by updating the interferometer (Fig. 2.6 sketches the main optical feedback control system) and developing a computer based algorithm able to produce a feedback action to control the stability of the experimental setup.

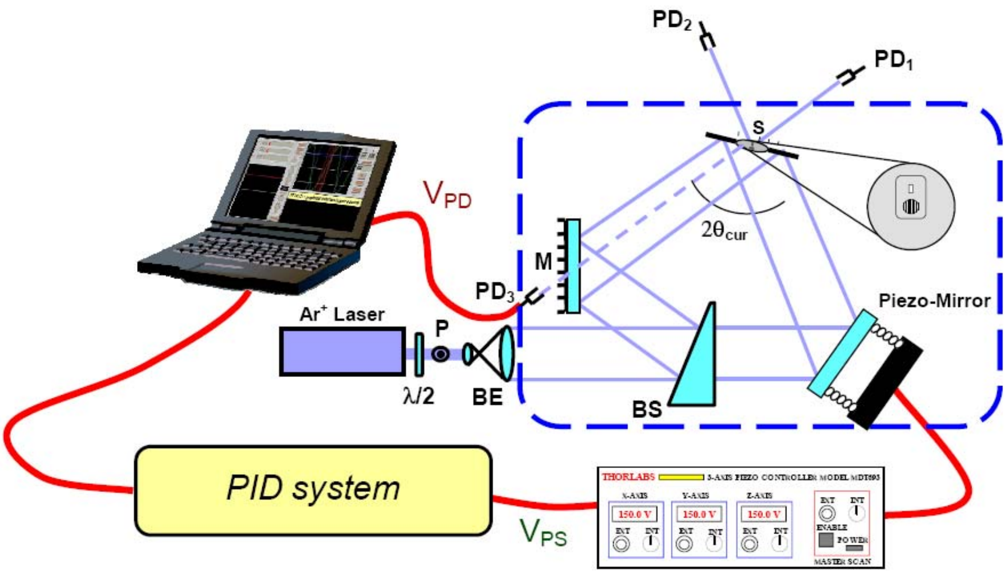

Figure 2.6: Feedback driven setup for curing POLICRYPS gratings. During the curing process, the control signal from the photodiode *PD3* is acquired by a computer and processed by a PID code, which sends a corrected driving voltage back to the piezo-mirror to stabilize the interferometric part of the setup

Where the necessity of an additional grating, specific to the recording, is concerned, for the present work we have used a commercial reference grating because it was necessary to test the reliability of the technique; in the future, however, for the fabrication of a particular POLICRYPS of good quality, a previously cured POLICRYPS of suitable pitch can be used as reference, independently of its quality. As for driving of the PZT mirror a personal computer was used to implement a typical PID (Proportional, Integral, Derivative) algorithm, commonly exploited to solve this kind of problems. For this purpose, LabVIEW software seemed at a first glance to be the best choice. Unfortunately, due to its long response times, the obtained code revealed ineffective for our aim. Indeed, the system was not able to follow typical, very fast, instabilities of the optical setup. We decided therefore to develop a home-made source code in C++ language, whose low level instruction set enabled to obtain a more satisfactory result. The flow chart of the code consists of a calibration stage and a three steps cycle. During calibration, the computer sends a voltage ramp (*VPS* from 0 V to 150 V) to the piezo mirror and acquires the resulting sine-like behavior of *VPD* versus *VPS*; afterwards it selects the first linear region in the obtained *VPD* curve (the one corresponding to the lowest possible *VPS* values). By choosing the central value of this region and feeding the piezo mirror with the corresponding *Vconst* voltage, the computer "sets" the optical system in the optimal region of operation for the PID algorithm. The cycle is conceptually very simple: the signal *VPD* coming from the photodiode *PD3* is acquired by the computer, processed using the PID system and used to drive the piezo mirror.

During every cycle, the difference $\Delta V = V_{PD} - V_{setpoin}$ is calculated, where $V_{setpoint}$ is the first voltage value acquired from *PD3* after the calibration stage has been completed, and represents the value which we want to stabilize the system at. The difference ΔV (called "error") corresponds instead to the actual deviation of the system from its working point and, as such, it must be compensated by modifying the piezo mirror position.

This is achieved by applying to the piezo system the instantaneous voltage:

$$V_{PS} = P \cdot \Delta V + I \cdot \Delta V \Delta t + D \cdot \frac{\Delta V}{\Delta t} + V_{const} \tag{4}$$

where Δt is the time duration of the single cycle and in our particular case it has been chosen equal to 1 ms, corresponding to the highest working frequency of the used piezo system (1 kHz). The difference between *VPS* and *Vconst* constitutes of three corrective terms which introduce respectively a first contribution proportional to the error ΔV, a second one proportional to its time integral and a third one proportional to its time derivative. *P*, *I*, *D* represent the gain parameters which govern the influence of each term and are carefully determined experimentally by utilizing an empirical procedure; good operation of the feedback action strongly depends on this choice. From a physical viewpoint, the meaning of these terms is clear, and this gives some advice on the order of magnitude of their parameter values. The proportional term (*P*) provides the main contribution to the control action because it has a direct influence on limiting the error: the more the error, the more the control action. The choice of a too high *P* value can however induce problems of overshoot, downshoot and "ringing" behavior of the system. These problems are mitigated by the influence of a derivative (*D*) or damping correction. This term is proportional to the rate of the error ΔV and tends to damp the drastic changes introduced by the proportional term. The correction given by a *PD* system is important to solve overshoot and ringing problems, but these two parameters have a slight influence on the correction of a "steady-state error", intended as the long term difference between the actual value and the setpoint value. An integral gain (*I*) represents the optimal solution for this kind of error since it takes into account a summation of errors over a long time interval. Hence the action of this term will keep increasing (or decreasing) until the error is made negligible.

2.4 Experiment

In order to check the reliability of our control system, we have performed a series of experiments in different experimental conditions. In previous investigations on the beam coupling effect which takes place during the curing process of POLICRYPS15, cares were taken to enhance the setup stability: A general reinforcement of all optical holders and the employment of a thermo-acoustic isolating box were adopted. For the present test, we proceeded by eliminating, step by step, all these remedies, verifying each time the effective performances exhibited by the new stabilization system. We started by eliminating reinforced holders, and assembled a new setup with standard optical posts and holders (from Thorlabs) which reproduced typical conditions commonly found in optical laboratories. The presence of the isolating box, as previously reported, reduced the influence of stochastic noise only in presence of a good control of experimental conditions; If the setup is realized with standard hardware and no particular care is adopted in preventing all kinds of noise around the optical table, this result cannot be expected. Fig. 2.7 represents a comparison between two stability tests performed in presence of the box, with the feedback action on and off, for the same time duration of 1000 sec.:

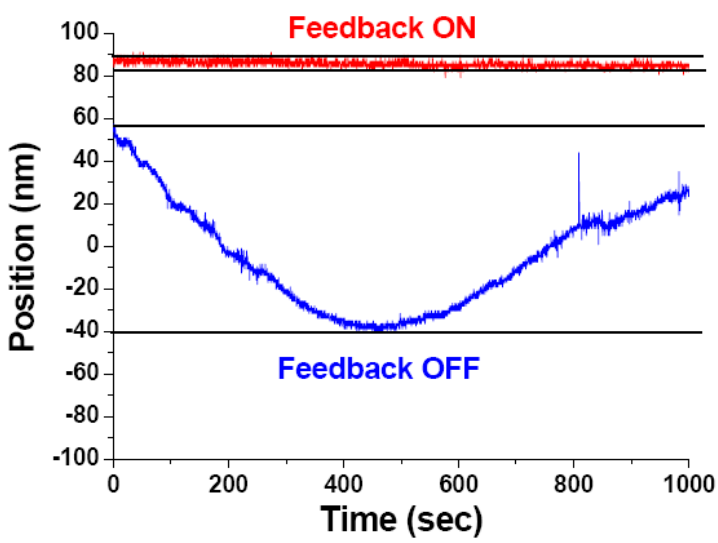

Figure 2.7: Typical time behavior of the spatial displacement of the test grating with respect to the curing pattern in presence of a thermo-acoustic isolating box. With feedback action on (upper curve), the system is stable (within the limits of the piezo-system accuracy). When the feedback action is off (lower curve), it is possible to recognize the action of the isolating box which prevents the stochastic jitters; this box turns out however to be ineffective where long term fluctuations are concerned.

The calculated displacement (in nm) whom the test grating (and hence the sample holder) undergoes during oscillations is reported. The upper curve is the result obtained in presence of the optical feedback control and shows a satisfactory degree of setup stability, the amplitude of the curve corresponding to the experimental accuracy of the employed piezo system (6-7 nm). Where the lower curve (no feedback action) is considered, it is evident that the presence of the box effectively limits the amplitude of the stochastic noise jitter; however the box turns out to be completely ineffective for correction of mechanical relaxations, which contribute to long term fluctuations. A confirmation of the fundamental importance of the feedback action is given in Fig. 2.8; in this case, during the experiment, we turned off this action and continued to monitorize the behaviour of the setup.

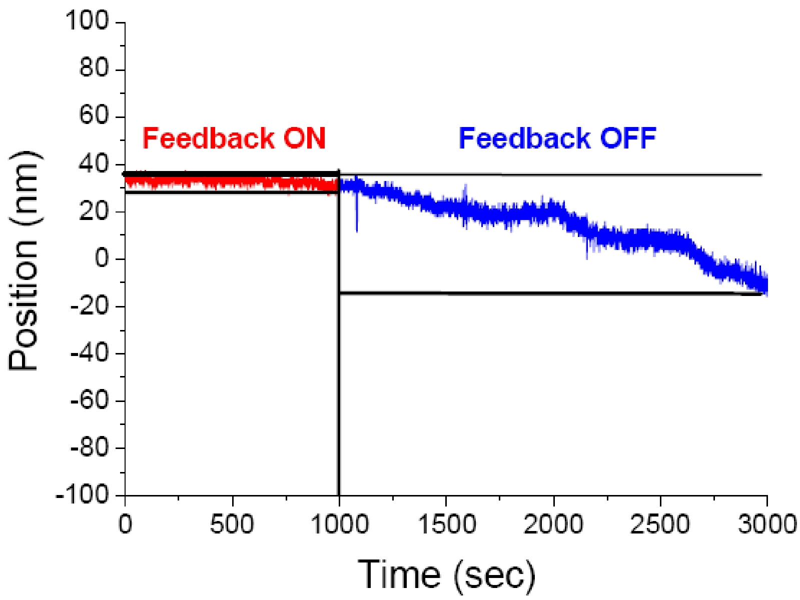

Figure 2.9: Typical time behaviour of the spatial displacement of the test grating with respect to the curing pattern in presence of a thermo-acoustic isolating box. If the feedback action is turned off during the curing process, long term fluctuations emerge, confirming the importance of the control action of the feedback system.

A drastic variation of the slope of the curve appears, which confirms the effectiveness of our control method. A second experiment was performed in the absence of the isolating box. Fig. 2.9 reports results obtained in presence (upper curve) and absence (lower curve) of the feedback control action: in the latter case, we have both large instantaneous jitters and long term fluctuations.

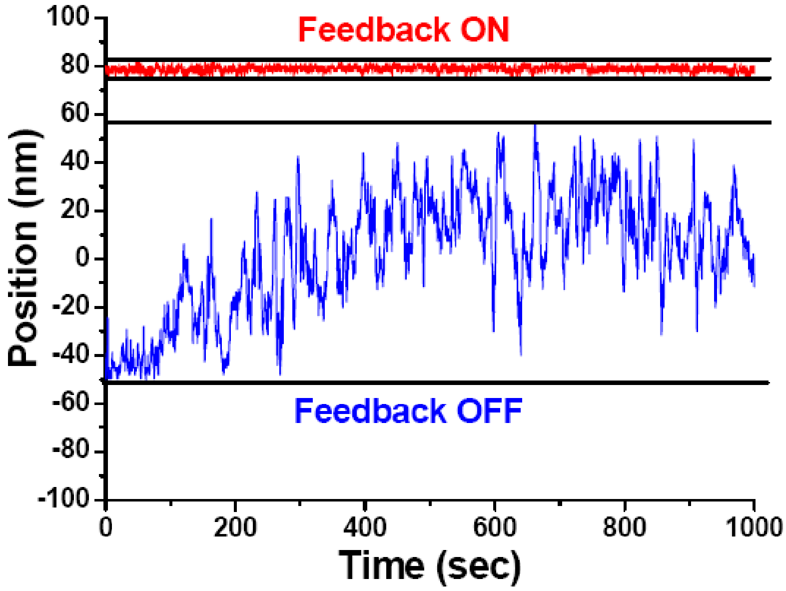

Figure 2.10: Typical time behaviour of the spatial displacement of the test grating with respect to the curing pattern in absence of a thermo-acoustic isolating box. Also in this case the feedback action is a key element in the stability of the system (upper curve). When the feedback action is off (lower curve), we can observe both stochastic jitter and long term fluctuations of the setup position.

Finally, the same experiment has been repeated switching off the control action during the curing process.

The result (reported in Fig. 2.10) shows that, after the turning off point, both the jitter and the long term fluctuations emerge denoting a general worsening of the system stability.

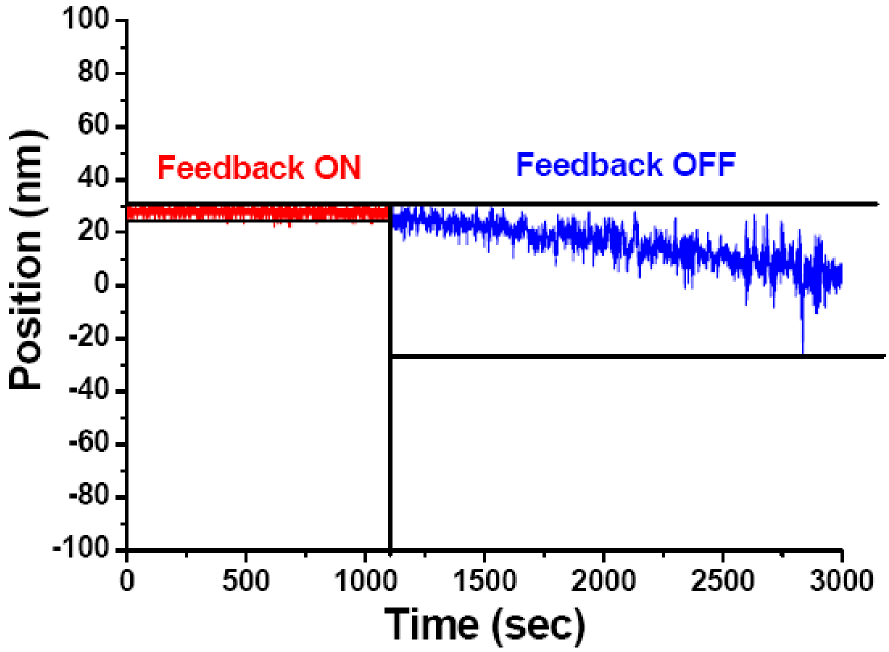

Figure 2.10: Typical time behavior of the spatial displacement of the test grating with respect to the curing pattern in absence of a thermo-acoustic isolating box. It can be observed that turning off the feedback action during the curing process, both jitter and long term fluctuations emerge, thus confirming the importance of the feedback control action.

These results are particularly encouraging, since they definitely demonstrate that, in presence of a feedback control action, high precision holographic experiments can be realized with no need of further particular (and eventually troublesome) stability remedies.

2.5 Conclusions

In this chapter we have reported the features of a novel technique which allows an *in situ* control and stabilization of an interferometric setup. We have exploited this technique to stabilize the process of fabrication of POLICRYPS diffraction gratings. The peculiarity consists in the “in situ” control mechanism, which has been obtained by using a reference diffraction grating that checks, in real time, the stability of the setup via a two-beam coupling effect. Experiments have been performed to verify the effectiveness of the new technique; in particular we have investigated the setup stability features both in presence and absence of a thermo-acoustic box covering the intereferometric area, which had shown a quite good stabilizing action in previous experiments. With the feedback control action on, the system exhibited an excellent degree of stability (either with or without the isolating box) limited only by the accuracy of the used piezo system. The same experiments, performed in the absence of the feedback action (with and without box), underlined the lack of stability of the system: In this case, an instantaneous stochastic jitter and a long term fluctuation of the sample holder position was recognized. While the jitter could be easily removed by using an isolating box, this care turns out to be completely useless for the suppression of long term fluctuations. Advantages of our system can be resumed as follows:

a) No additional optical sources or lock-in amplifiers are introduced and the setup is not cumbersome at all.

b) Resolution is only limited by the sensitivity of the PZT mirror. By using a high resolution one, the stability of the system can be further improved.

The easy implementation of the technique and its evident features represent, in our opinion, a valid reason to use it in all experiments where a high (both short and long term) stability is required for the optical setup.