SMART SENSORS FOR RESIN FLOW AND COMPOSITE CURE MONITORING

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SUMMARY:

A procedure for monitoring the resin flow front advancement in the RTM process based on an array of optical fibres placed in the preform has been developed. The system is robust and adaptable to any part geometry.

Besides, the operation of a miniature optical fibre sensing probe for resin cure monitoring is described. The head of the probe can detect the changes in the refractive index of the resin due to cure shrinkage, and its temperature, has an internal reference to compensate any external disturbances, such as power drifts or macro and microbending in the optical fibers, that previously restricted the use of this technique to laboratory environments.

Both functions are carried out by a single multitask optoelectronic system developed by the UPM, which is also able to monitor up to sixteen embeddable optical fibre probes with six sensors each for strain/temperature measurements of in-service composite structures. The system operates under Labview control.

KEYWORDS: Fiber optic sensor, RTM, cure monitoring, smart processing.

1. INTRODUCTION

Improvements in quality of composite parts, accompanied of production costs and time cycle reductions, may be attained by combining reliable real time sensors to efficient control algorithms, based on accurate models of the processes and/or machine learning methodologies.

This is the global approach for the PERFECT Project (Process Efficient Regulation for Economical Composite Technologies), a Brite-Euram project that started in December 97, involving a number of aeronautical European industries and research centres. The project focuses on autoclave and RTM processes, as the most currently used technologies for manufacturing thermoset composites structural components.

Thermocouples are nowadays the only used sensors during the curing cycles; more information on the evolution of key properties, like degree of cure or viscosity, is required before any practical attempt of ‘smart processing’ may be implemented, to take into account raw materials variability, different tooling and autoclave loading, etc.

This paper focuses on the developments done at the authors´ institutions on Fiber Optic Sensors (FOS) to monitor resin flow and cure; other partners are simultaneously working on dielectrics and ultrasonic sensors, enabling a comparison of results and characteristics of the different kinds of sensors.

2. FIBER OPTIC SENSORS EMBEDDING

Optical fibres are guides of light, usually made of high purity silica, with a diameter about ten times that of a classical E-glass fiber; Optical fibre sensors for different purposes have been developed [1], and a single fiber works both as sensor and information path. Their small size, low noise, non-electrical nature, etc., make these kind of sensors very attractive for Smart Structures applications [2].

If adequately oriented, optical fibers may be easily embedded into the laminate without any detrimental effect on its mechanical strength. Ingress/egress of the optical fiber from the composite structure is still a main issue if the sensors must remain operative after curing, and the part need to be trimmed in all its edges. This is not the case for process monitoring, and optical fibers can ingress the lay-up through the venting ports, in RTM, or through the sealing paste in the autoclave process.

Laminates have been manufactured by RTM with embedded Bragg gratings, to measure their residual stresses. The weakest point uses to be the fusion-splices, which need to be reinforced. In a previous project, Bragg gratings manufactured at the UPM were also embedded while manufacturing a wind turbine blade, to measure the in-service stresses, with a high rate of survivability [3], [4]. A complete discussion on the optical response of a grating when embedded into thick CFRP was recently done by the authors, and will not be repeated here [5].

3. RESIN FLOW SENSORS FOR RTM PROCESS

RTM process is a highly automated procedure that promises significant costs reductions of composite parts. However, the high fiber volume required for aerospace structures implies very dense preforms, which difficult the resin flow; if not adequately programmed, resin get gelled before filling up completely the mould. Numerical models of the resin flow are available, with different levels of accuracy, but presently, to a large extent, developing a mould for RTM is still a costly empirical process solved by trial and error.

The proposed system is a tool to get some insight of the process sequence, by monitoring the resin flow front movement. Our system is based in an array of standard optical fibres. The only proposed alternative approach is based on an array of electrical wires, checking the change of electrical resistance at the cross points due to the resin arrival [6].

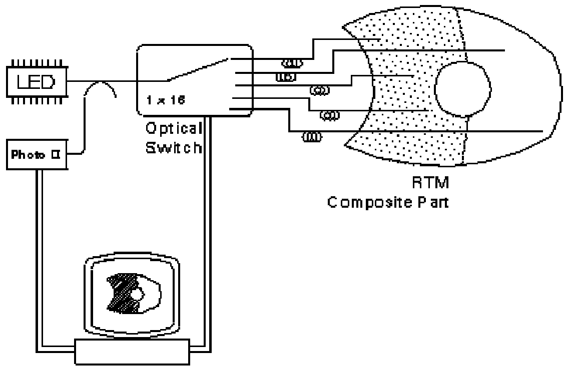


Fig. 1. Schematic of the experimental set-up to monitor resin flow

Figure 1 sketches the system under tests for monitoring the resin flow front during resin infiltration. An array of 16 optical fibers is distributed in the dry preform, ending at different predefined positions. Light is launched into the fibers through an optical switch (100 msec. commuting time). About 5% of this light is backreflected at the flat end-face of the optical fiber, according to Fresnel law, when air is at the interface. This reflection drops to almost zero when resin arrives, due to the better matching of refractive indexes. A computer controls the switch position among the different optical fibers, comparing the time of resin arrivals to the model predictions.

The proposed system is robust and adaptable to any part geometry; fibers will remain embedded into the structure without any detrimental effect. They may later be used for cure monitoring or health monitoring purposes, if the optical fiber were prepared also for that mission. Preliminary tests are satisfactory; only the occasional presence of bubbles in the resin front causes troubles in the measurements.

4. FIBER OPTIC SENSORS FOR CURE MONITORING

4.1. Cure monitoring overview

The cure process of thermoset composites may be accurately tracked in a laboratory environment by a variety of instrumental techniques, but still there are not robust procedures to be used in a factory environment. This issue has been throughfully discussed at the literature [7], [8], [9]. The development of reliable optical sensors has the attractiveness that light may go in and out of the part through optical fibres, allowing a remote control with little interferences.

Several fibre optic based techniques have been proposed for resin cure monitoring: evanescent wave interactions, transmission spectrum analysis, Fresnel reflection, fluorescence, FT Raman spectrum measurement, etc. Changes in the IR spectrum of the resin are a good indicator of the cure evolution, and remote FTIR spectroscopy seemed the most attractive approach, because the information is spectral, and not subject to changes due to intensity loss. Standard optical fibers are not transparent to mid-IR, but still sensitive changes are found at the near IR band (4000 to 9000 cm-1), for epoxy and BMI resins.

Commercial probes based on diffuse reflection are available, but they are too bulky to be embedded. We have tried to develop a transmission-based single-fiber optic sensor, without success up to now because of poor repetitivity.

An alternative approach makes use of the changes in the refractive index of the resin that happen during the curing stage, due to the resin shrinkage. For a typical epoxy resin, refractive index increases from 1.45 to 1.52 for a fully cross-linked resin; temperature produces similar changes that need to be compensated. Several techniques may be used to detect this change [10]. Fresnel reflection is probably the simplest technique. A light source, a photodetector, an optical coupler and a cleaved optical fibre, are enough to monitor the evolution of the refractive index of the resin.

A sketch of a basic device is shown in Fig. 2: Light coming out from an optical source is launched into an optical fibre through a coupler. The tip of the optical fiber, cleaved very precisely, is immersed in the medium under analysis, in our case, resin. The interface core-resin acts as a sensor: most of the light that arrives to this surface pass through it, but a part of it is reflected back, in accordance with Fresnel law. The light reflected back pass again through the coupler and is detected by a photodiode. The relationship between detected power and refractive index is relatively simple.

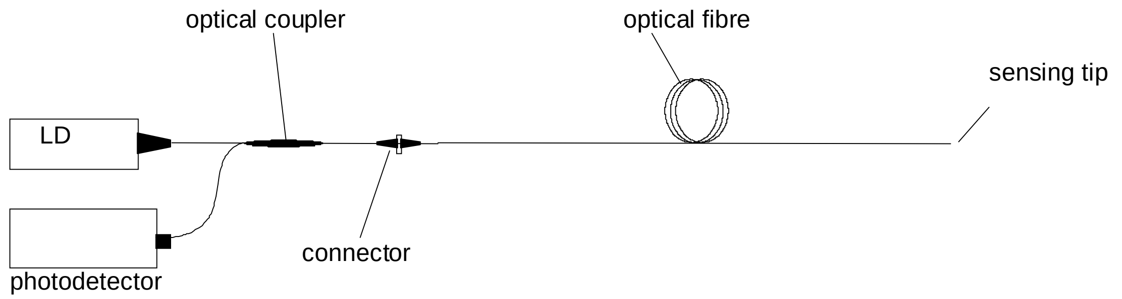


Fig. 2. Schematic of a Fresnel based curing monitoring system

It has been demonstrated an association between the refractive index with the degree of cure and the temperature of the resin [11], so it would be possible to use this technique to monitor the evolution of the cure processing. The use of standard 125 μm diameter singlemode optical fiber allows reaching remote zones of the composite part under analysis with extremely slight mechanical interference.

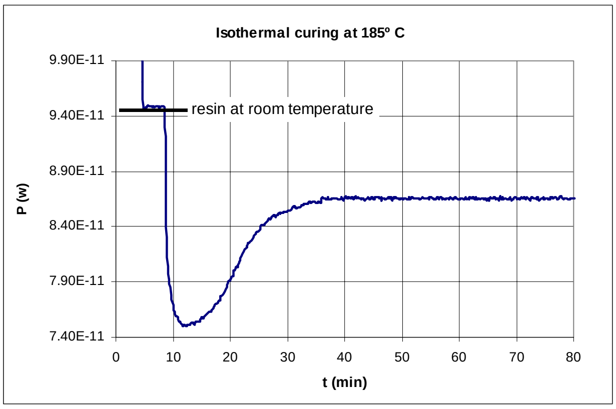


Fig. 3. Optical signal of a Fresnel based system during an isothermal curing

Unfortunately, this technique shows the same problem as any other technique based in light intensity measurements. Power drifts of the light source, unstable connections, output power variability in optical switches, mechanical perturbations in the optical path, due to macrobending and microbending of the optical fibre embedded into a composite laminate during the cure process limit its applicability to the highly controlled laboratory conditions. Furthermore, it would be necessary to have an accurate reading of the temperature at the place where the tip of the fibre is embedded, to compensate its effect on the refractive index of the resin.

4.2. Self -referenced refractive index and temperature monitoring probe

To overcome the previously mentioned issue, we have developed and patented a sensing probe that works succesfully to discriminate and compensate the effect of any perturbations on the signal coming from the sensing head. Intracore fibre Bragg gratings, optical devices which have proven their versatility and feasibility in many applications in the field of fibre optic based smart structures, having become almost an standard as embeddable strain and temperature sensors, are used in this case as very precise references to remove undesirable perturbations on the signal reflected back by the core-resin interface.

4.2.1. Fibre Bragg gratings overview

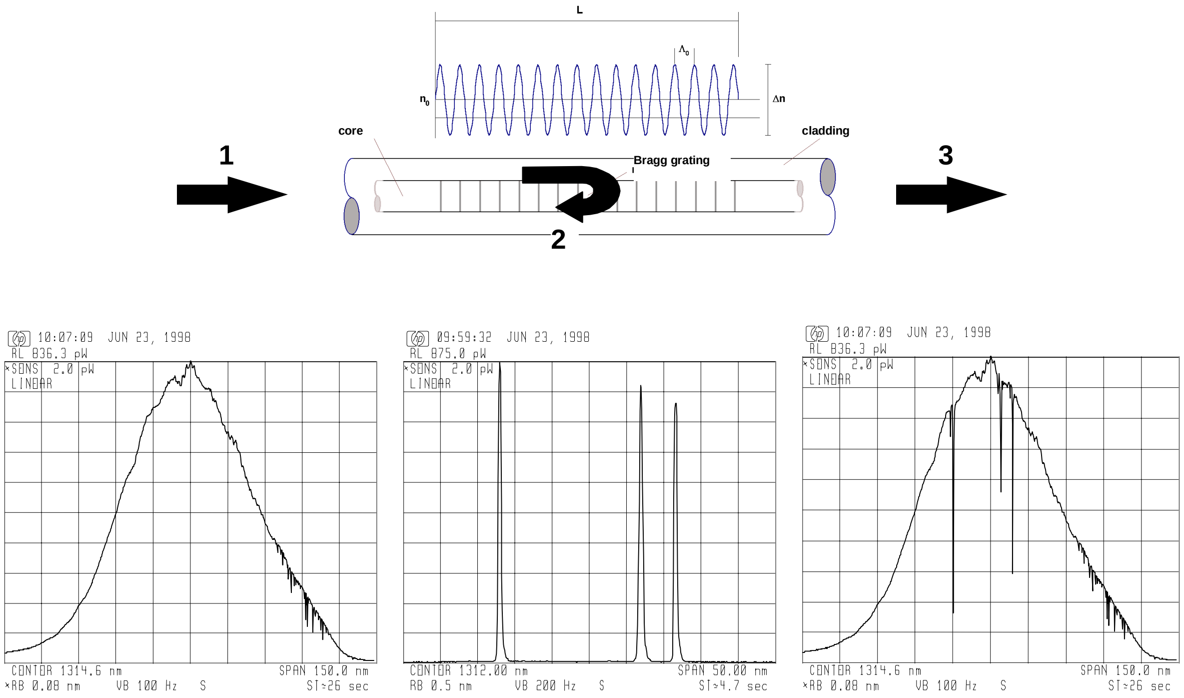
A fibre Bragg grating is a periodic modulation in the refractive index of the core of a single mode optical fibre, written along a certain length by an UV holographic pattern [12]. When a broadband light is travelling through the fibre, the grating promotes that a very narrow wavelength band is reflected back. The centre wavelength of this band can be easily represented by the Bragg condition:

$$\lambda_0 = 2n_0\Lambda_0 \qquad (1)$$

in which λ_0 is the centre wavelength, n_0 is the average refractive index of the grating and Λ_0 is the pitch of its periodical pattern.

Fiber Bragg gratings present a very interesting physical property: if the grating is subject to an uniform axial strain, or an uniform thermal increment is applied, the centre wavelength of the spectrum reflected by the grating will shift due to changes in the pitch and the refractive index, and such behaviour is completely linear. This characteristic, and the fact that several fiber gratings may operate independently in the same optical fiber, as long as their central wavelength do not interfere, have allow to consider this devices a serious alternative to the conventional resistive strain gages, and they have been presently integrated in a number of civil structures and advanced composite parts.

But strain detection in intelligent structures is not the only application of these devices: fiber Bragg gratings have revolutionize the optical fiber based telecommunications, and are intensively used as in-fibre optical filters, WDM's, integrated fiber optic amplifiers, and as stable wavelength references. The optoelectronic system proposed in this document is related to this last application.



(1) (2) (3)

Fig. 4. Schematic of a fibre Bragg grating and operating principle. (1) Intensity spectrum of a broadband source launched into the fibre. (2) Spectra reflected back by three fibre Bragg gratings. (3) Transmisive spectrum after passing the three Bragg gratings.

4.2.2. Hardware set-up and operating principles

The system proposed and developed by the UPM is similar to the basic scheme represented in figure 2, but includes two fibre Bragg gratings and the photodetector is substituted by an optical spectrum analyzer (OSA), which allows not only to detect the total power reflected back by the different devices of the optical path, but to separate the light reflected at different wavelengths. The Bragg gratings operate in this scheme as narrowband mirrors, which backreflect a constant percentage of the power launched through them. Therefore, the gratings are used to detect which is the amount of light power that reaches certain point of the optical path.

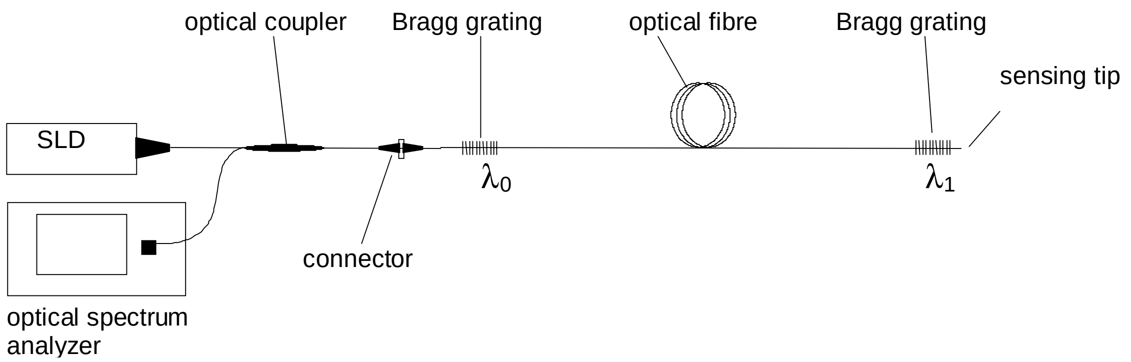


Fig. 5. Schematic of a fibre Bragg grating referenced system

The way in which the system operates is the following:

- Bragg grating 1 operates as the main reference of the system. While the power of the optical source remains stable, the optical spectrum analyzer detects the sum of the backreflections along the optical path, the reflection in the fibre-resin interface of the sensing head, and the spectrum of the grating 1. If any external perturbation is applied to the optical fibre, it causes a power drift that affects in the same way the power reflected by the grating and to the signal reflected in the fibre-resin interface. Therefore, it is possible to discriminate the variations of the signal due to the refractive index changes from those due to external perturbations.

- Bragg grating 0 operates as an auxiliary reference, and allows compensating power drifts due to instabilities of the source, or variable backreflections in the optical path due to optical switches, or unstable optical connections.

Fig. 6 shows a schematic of the spectrum received by the optical spectrum analyzer, and the contribution of each part of the optical system to the signal detected.

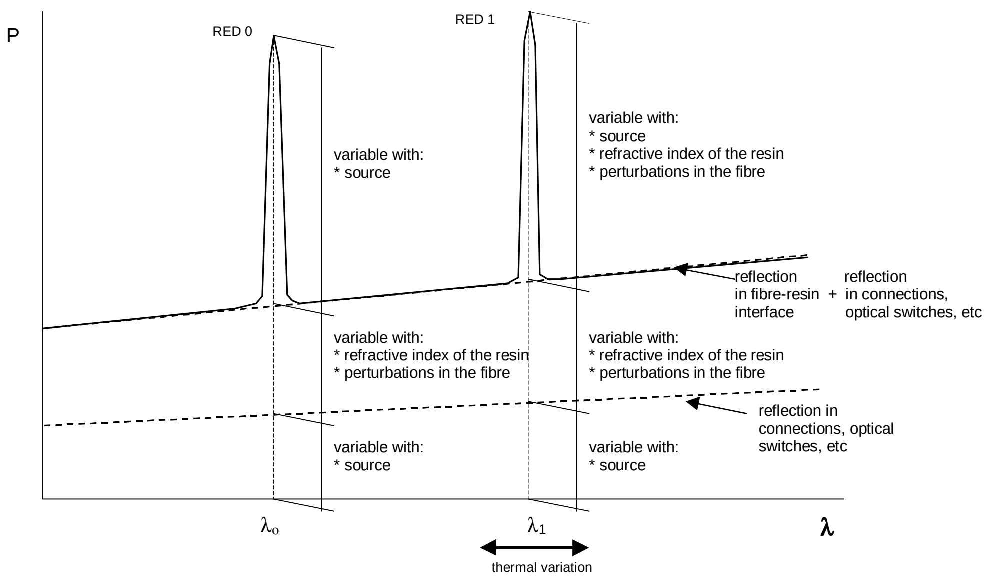


Fig. 6. Schematic of the different contributions to the spectrum received by the OSA.

An important additional advantage of the system proposed is that the same fibre Bragg grating placed near the cleaved tip to operate as internal reference, acts as a local temperature sensor, which allows calculating very accurately the effect of the temperature on the refractive index.

Fig. 7 shows an example of the optical detected by a conventional reflectometer, distorted by power drifts of the light source and external perturbations in the optical fibre, and the signal compensated by a double-grating compensating system: n_1, n_2, n_3 and n_4 correspond to the refractive index of four different fluids. The system is able to correct signal deviations which would correspond to refractive index variations higher than 0.5.

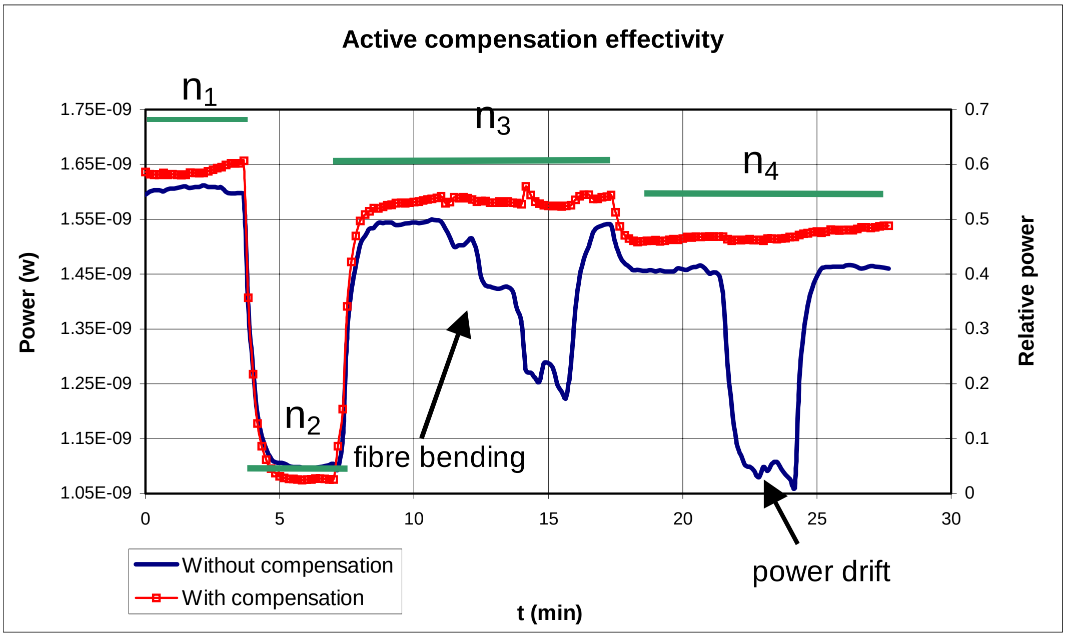


Fig. 7. Signal detected by a conventional reflectometer and signal compensated by a double-grating compensating system.

This technique is compatible with fiber Bragg grating strain monitoring systems and RTM resin flow detection optical fiber based systems, which allows the use of a single multitask equipment to monitor in-situ the manufacture of composite materials. The reference Bragg gratings, embedded into the structure, can be finally used as conventional strain sensors.

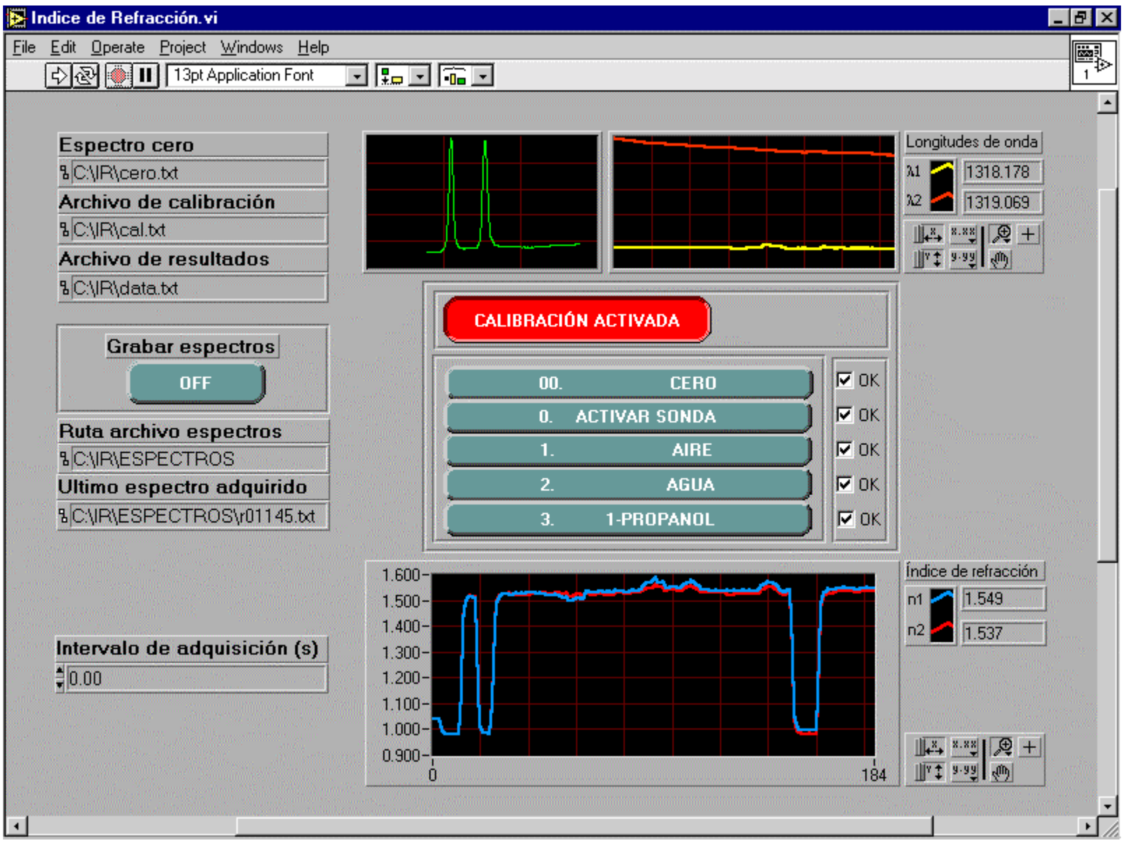


Fig 8. Window of the Labview based interface used for refractive index detection

5. CONCLUSIONS

Considerable research and development effort is being devoted to improve the quality and the reliability of the processes for manufacturing advanced composites, and to transform fixed and standardized cycles to intelligently controlled and optimized operations.

Optical fiber sensors has revealed as useful tools in several stages of the quality control of the manufacturing of composite parts: resin flow, refractive index and temperature monitoring, strain measurement. The systems and processes presented in this document allow an easy integration of these techniques in standard manufacturing processes, while the slight influence of embedded optical fibers in the mechanical properties of the composite material allows that fibers remain embedded during the active life of the part.

6. ACKNOWLEDGEMENTS

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