Research Article

Miniaturised Optical Fibre Sensor for Dew Detection Inside Organ Pipes

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A new optical sensor for the continuous monitoring of the dew formation inside organ pipes was designed. This aspect is particularly critical for the conservation of organs in unheated churches since the dew formation or the condensation on the pipe surfaces can contribute to many kinds of physical and chemical disruptive mechanisms. The working principle is based on the change in the reflectivity which is observed on the surface of the fibre tip, when a water layer is formed on its distal end. Intensity changes of the order of 35% were measured, following the formation of the water layer on the distal end of a 400/430 μm optical fibre. Long-term tests carried out placing the fibre tip inside the base of an in-house-made metallic foot of an organ pipe located in an external environment revealed the consistency of the proposed system.

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1. INTRODUCTION

Controlling the microclimate within museum, art galleries, and churches is increasingly recognised as an essential feature in the protection and preservation of invaluable works of art [1, 2]. Important requirements for this application are of a very low environmental impact, so as to assure minimal interference with the visualization of the exposed works of art by visitors, continuous monitoring and complete safety in operation. The high degree of miniaturisation, easy handling, and absence of electric contacts make the utilisation of optical sensors in this field very appropriate.

Optical fibre sensors originated in the eighties and their development are still expanding since they find their application in many fields ranging from environment to medicine and industry [3, 4].

The protection and maintenance of works of art in the museums and churches is a task which has always been pursued but only in the last decade recent works have emphasised the relevant role played by the microclimate.

Knowledge of the microclimate, by means of an analysis of the environmental parameters, allows the evaluation of the

level of risk to which the art objects are exposed. Clearly, this can trigger actions directed at minimising the causes of risk and at insuring the attainment of more appropriate conditions of preservation. Moreover, it is obvious that, after their definition and achievement, these conditions should be kept as constant as possible, notwithstanding the unavoidable changes induced by the external surroundings.

The pipe organ and its music are important parts of the cultural heritage of Europe. The organ, with its facade architecture and sound, is a multimedia and multidisciplinary object. The organ heritage found in all countries of Europe includes more than 10 000 historical valuable organs.

The organ contains many different types of materials like different types of wood, leather, different types of lead-tin alloys, from pure lead to almost pure tin, brass, and iron. It also contains a complex system of moving parts and the bellows and the wind channels need to be airtight. This makes the organ to an object very sensitive to microclimate changes and harmful environments. The organ can be unplayable if only one of the materials or functions just mentioned is responding to the environment in a negative way.

Recently, it was shown that the escalating problem of corrosion inside organ pipes is caused by organic acids, especially acetic acid, emitted from the wooden parts in the organ [5–7]. The organic acids enter into the pipe foot and create a corrosive environment inside the foot. The formation of a corrosive environment in the pipes is mainly dependent on the pipe metal alloy and the temperature and humidity in the organ. High humidity and condensation can create an environment where development of mould on the wooden parts can take place and it can also cause corrosion on the iron parts of the organ in addition to the pipe corrosion. Also, frost crystals formed in oxidised pipes in unheated churches may cause mechanical damage to them.

For the preservation of the organ cultural heritage, there is a great need for monitoring the climate conditions in the organ and in the pipes especially after an organ restoration or a change of the heating system and the ventilation conditions in the church.

In the framework of the European project SENSORGAN (sensor system to detect harmful environments for pipe organs) which has the objective to make available new instrumentation for monitoring and detection of harmful environments for pipe organs through development of sensors for real time measurement, a miniaturised optical fibre sensor for detection of dew formation, or condensation, inside/outside organ pipes is under progress.

The working principle of the sensor, its design and the laboratory characterisation is here described.

2. EXPERIMENTAL

The working principle of the optical fibre sensor is based on the change in the properties of the optical transmission of an optical fibre. On the basis of the input requirements, two different configurations were designed and tested making use of a single fibre.

In the first configuration, the formation of the water layers associated to the dew point occurs along the fibre which is deprived of the cladding. The change in the refractive index associated to the formation of the water layers provokes a change in the transmission properties of the optical fibre, with an increased amount of light which is directed out of the fibre. In order to increase the sensitivity of the approach (i.e., an increase in the losses associated to the change of refractive index), the fibre is U-shaped in correspondence of the region where the cladding is removed. Practically the fibre is fixed on metallic cylinders by means of a polymeric glue, and the curved region is polished until the clad of the fibre is fully removed. Two different silica fibres were tested in this configuration, with a core diameter of 1 mm and 200 μm , respectively (3M, HCPM0200T). The fibre was then connected to a laser diode (Roithner Lasertechnik, LDM635/3-OLU) on one side and to a photodetector (TAOS, TSL14S) on the other side.

The second configuration bases its working principle on the change in the reflectivity of a 400/430 μm optical fibre (3M, HCPM0400T), following the formation of a water layer or ice crystals on its distal end. It is clear that

FIGURE 1: Sketch of the optoelectronic configuration used to measure the reflectivity changes which occurs at the distal end of the optical fibre. LD: laser diode; MPD: module to monitor the laser diode emission; P: voltage control to keep the laser diode emission constant; PD: hybrid photodetector; OUT1-3: signal output of the light-to-voltage converters.

this configuration is simpler and more compact. A similar configuration was successfully adopted for the continuous monitoring of respiratory rate, measuring the change of reflectivity at the fibre end due to the change in the condensed humidity from the airways during respiration [8]. Two optical fibres (3M, HCPM0200T, core/clad diameter: 200/230 μm) allow the connection of the sensing fibre to the laser diode (Roithner Lasertechnik, LDM635/3-OLU) and to the photodetector (TAOS, TSL14S).

Figure 1 shows schematically the optoelectronic system used for the interrogation of the fibre in the case of the second configuration. It has three channels that are independent from each other but share the same laser diode (LD) as light source so that three different locations can be monitored at the same time. The monitor photodiode (MPD) is inserted in the feedback loop of the laser diode (LD) driver, so that constant power emission is achieved through the voltage control (P), and hybrid photodetectors (PD1-3) are used, which provide direct light-to-voltage conversion (OUT1-3). Then the voltage signal is converted by an analog-to-digital converter connected to a laptop.

Commercial sensors were used to measure the temperature (Analog Devices, AD22100) and the relative humidity (Honeywell, HIH4000-001).

3. RESULTS AND DISCUSSION

In order to test the two different configurations, an apparatus was realised capable to change, control, and measure the temperature and the relative humidity of the region in proximity of the sensing point. The sensing part of the optical fibre is fixed on an aluminium block, the temperature of which is regulated by means of a Peltier cell. In this way, it is possible to reach the dew point with the formation of water droplets or of a water layer on both the block piece and the sensing part of the fibre.

A software program developed under LabView allows the acquisition of the signal coming from the optical fibre and

from the sensors for humidity and temperature as well as the driving the Peltier cell.

Preliminary tests showed a better sensitivity in the case of the reflectivity-based configuration. With this configuration, intensity changes of the order of 35% were found, whereas in the case of the U-shaped fibres the changes were not greater than 20%.

Therefore all the further tests were made with the reflectivity-based configuration. Figure 2 shows the optical fibre deprived of the jacket located on the aluminium block. The water drops formed on the aluminium block due to the condensation are clearly visible. Figure 3 shows the typical results obtained when the temperature of the block was changed from 25°C to 5°C and back again to 25°C. The relative humidity changes from 40% to roughly 90%. The signal coming from the optical fibre sensor is normalised with respect to its value in dry conditions. The optical signal, after a slight increase, starts to decrease as a consequence of the formation of the water layer on the fibre tip. A stable value is reached and this value persists also after the increase of the temperature, since the humidity on the fibre tip is still present. After roughly half an hour, the water is completely evaporated and the signal coming from the fibre comes back to the initial value. As it can be seen, the change of the signal from the fibre is of the order of 35%. During all the experiment, the external temperature and the external relative humidity remain practically constant and equal to 24°C and 38%, respectively.

In order to evaluate the performance of the sensor in a situation closer to the real one, the system was characterised by placing the sensing fibre inside the foot of a metallic organ pipe built at the Göteborg Organ Art Center. The organ pipe was placed in an in-house-made thermal box. Three sensors were placed at the same time in order to evaluate the reproducibility of the results and a suitable in-house-made spring was used to keep the fibre ends in place (tangent to the pipe's inner surface) (Figure 4). This spring was designed so as to be used also in real conditions in organs inside churches, where the access to the internal surfaces of the organ pipes is performed through a small opening located in their foot.

Thermal cycles were performed by placing dry ice in the thermal box until the dew occurred inside the inner surface of the pipe and then removing it until the equilibrium with the environment was reached. These steps were repeated several times. The sensor outputs of the three fibres, normalised to their value in dry conditions, are shown in the upper graph of Figure 5. In the lower graph the temperature and the relative humidity recorded inside the pipe foot are shown. Also in this case, as observed in Figure 3, the responses of the optical sensors are well correlated with the changes in temperature and in humidity, with the optical signal which decreases in correspondence of a temperature increase and of an RH decrease. It is quite important to observe that the behaviour of the three optical sensors is very similar; the differences which are observed can be ascribed to the different locations inside the metallic organ pipe characterised by slightly different distances of the fibre tip from the metallic surfaces. In any case, the reproducibility of the three sensors can be considered satisfactory in view of the

FIGURE 2: The optical fibre tip deprived of the jacket and fixed on the surface of an aluminium block; the photo was taken after the condensation took place, and the water drops are clearly visible on the aluminium surface.

FIGURE 3: Response curve of the optical fibre sensor following a decrease of the temperature of the aluminium block from 25°C to 5°C and back again to 25°C. The graph shows also the tracings of both the temperature and the relative humidity of the aluminium block (named internal RH and internal T, resp.) and of the external environment (named external RH and external T, resp.). The left y-axis is related to the optical signal, whereas the y-axis on the right is for the temperature and the related humidity.

FIGURE 4: The metallic foot of the organ pipe with the three optical fibre sensors. The inset on the bottom/left shows how the metallic spring keeps the three fibre tips in contact with the pipe's inner surface.

FIGURE 5: Laboratory characterization of the optical system carried out by placing the base of the organ pipe with the sensing fibres inside a thermal box. On the top, the response curve of three optical sensors placed inside the metallic organ pipe are shown. On the bottom, the temperature and relative humidity curves are shown.

FIGURE 6: Long-term characterization of the optical system in external environment. On the top the response of the sensing fibres inserted inside the base of the organ pipe is shown; on the bottom the external relative humidity and the external temperature are shown.

application of the sensor in real environment and an alarm threshold for the water condensation can be established in correspondence of a 15% decrease of the optical signal exhibited in dry conditions.

After the laboratory characterisation, the system was exposed for a longer period in external environment inside a weather screen with open louvers. The optical system was exposed together with the sensors for temperature and relative humidity. Figure 6 shows the results for a six-day measurement. The sampling of the optical sensor was made every 15 minutes and recorded in a data logger. The sensor output, the external temperature, and the external RH have been recorded. The periodic trend is clearly correlated to the cycles of the day and of the night. The optical sensor responds equally well to dewing and frosting, as it was recognised by inserting the fibres inside a freezer cell, -24°C . The output drop for ice crystals is similar to that for droplets.

This behaviour fulfils perfectly the requirements for an *in situ* application of the sensor inside the organ pipes in the church; the achievement of a dangerous level of condensation on the internal walls of the pipes can be identified with a threshold level corresponding to a 15% decrease of the signal exhibited in dry condition.

One of the main problems which generally affects intensity-based sensors is given by fluctuations/losses not dependent on the measurand-induced changes, such as source fluctuations (avoided in the present case by the use of a diode laser driven at constant power) or changes in the fibre transmission induced by temperature changes

or fibre bending. This problem is less effective in this application due to the binary nature of operation (dew or not dew). Even if the device exhibits a correlation with RH in a certain range, it must be pointed out that it is not sufficiently accurate as analog sensor, at least in this simple configuration, without any reference channel to compensate down-lead fluctuations in loss and without any calibration. Nevertheless, the particular application, for which such a device has been developed, requires to monitor the occurrence of an excess of RH ($>90\%$), where the output drops certainly below 80% of the value attained in dry conditions. Then, once installed (from then, one can reasonably expect small loss fluctuations), it can be reliably used as ON/OFF sensor simply by fixing a suitable threshold, proportional to the value measured at low RH. Moreover, the simultaneous use of the three sensing points with the three different fibres can be used as safety redundancy; the concordance of the output from the three fibres can be used as intrinsic control of the sensor reliability.

4. CONCLUSIONS

The described optical sensor is capable of monitoring continuously the water condensation and the formation of ice crystals inside organ pipes. Although not tested yet, it should properly work also in the presence of acetic and formic acid released by the wood deterioration, as it occurs inside the organ pipes. As a matter of fact, the transduction of the signal occurs at the interface quartz/air of the optical

fibre, and thanks to the well-known chemical resistance of the quartz fibre, this surface should be unaffected by the presence of weak acids such as acetic and formic acid. In addition, the condensation may occur earlier for the presence of hydrophilic metal oxides. Being in direct contact with the target surface, it is able to monitor what happens inside the organ pipe. The thorough characterisation in the laboratory and the long-term characterisation in external environment showed the reliability of the optical sensor and the efficiency of the adopted working principle. The next step will be the performance of real tests on the historical organ in the Minor Basilica of St. Andrew the Apostle in Olkusz, Poland.

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