Laser sensors for continuous monitoring of dimensional response of wooden objects in situ

Ł. Bratasz, R. Kozłowski
Laser Sensors for Continuous In-Situ Monitoring of the Dimensional Response of Wooden Objects

ŁUKASZ BRATASZ, ROMAN KOZŁOWSKI

Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, ul. Niezapominajek 8, 30-239 Kraków, Poland, e-mail: nkozlow@cyf-kr.edu.pl

Abstract

The application of triangulation laser displacement sensors to the continuous in-situ monitoring of the response of wooden cultural objects to variations in temperature and relative humidity in their environment is reported. The sensors are robust, fast, and precise, provide non-contact measurements, and are capable of operating in the field. They have been applied to monitor the response of the altarpiece in the church of Santa Maria Maddalena in Rocca Pietore, Italy, to fluctuations in temperature and relative humidity caused by the use of the heating system. Complex short-, medium- and long-term responses of a variety of carved wooden elements have been recorded.

Introduction

Fluctuations in ambient relative humidity (RH) are considered to be one of the main factors that contribute to the deterioration of wooden objects. Wood responds to these fluctuations by gaining moisture when the humidity is high, or losing moisture when the surrounding air is dry. The moisture content in wood exposed to a given temperature and RH eventually attains a constant level termed the equilibrium moisture content (EMC). The relationships between the RH and EMC at constant temperatures (water sorption isotherms) have been determined for many typical wood species [1]. For most practical purposes, EMC values for a given temperature and RH may be approximated by an empirical formula, which is applicable to any species of wood and is given in handbooks on wood technology [2].

Dimensional change is perhaps the most important consequence of moisture sorption by wood. Wood shrinks as it loses moisture and swells when it gains moisture. Wood is anisotropic and its moisture-related dimensional changes vary in its three principal anatomical axes – longitudinal, or parallel to grain, radial and tangential. The most pronounced moisture response is in the tangential direction, where wood swells up to 80 times more than in its longitudinal direction, in which there is negligible response. In the technical literature it is common to express dimensional change in wood as a total shrinkage percentage, from its fully swollen ‘green’ condition to the oven-dried material. More useful information is provided by swelling isotherms, which express the amount wood swells or shrinks at different RH levels for a constant temperature. The dimensional change is obviously determined separately for each anatomic direction and for each wood species. Considerable variation in shrinkage occurs for individual pieces of wood, even from the same species and from the same locality. Therefore it is
impossible to predict the dimensional change of a given wooden object accurately and the empirical formulae given in the wood handbooks can be used merely to estimate the change [3].

A noteworthy effect of the dimensional change of wood is the resulting high stress within the material, which can cause significant damage. If a relatively dry wood is restrained from natural swelling in high RH, it can experience plastic deformation in compression with resulting crushing of the internal wood structure and buckling. In turn, if the wet wood is restrained from natural shrinkage on return to low RH, it will experience tension leading to irreversible stretching and eventual cracking. Restraining may be built-in and result from a rigid construction restricting movement, but wood can also experience internal restraint. The latter kind of restraint is generated by the anisotropic structure of the wood or by a dynamic gradient of EMC when the exterior part of the wood responds more quickly than the interior to a change in RH.

The past 15 years have seen much interest in the response of wooden cultural objects to changes in ambient RH. Mecklenburg, Erhardt and Tumosa have undertaken substantial investigations to quantify mechanical properties and swelling response of materials that constitute painted wooden objects, such as hide glues, gesso, paints and varnishes [4]. By relating the independent RH responses of each of these materials, particularly by determining the effect of the wood substrate on paint materials, the authors were able to determine the allowable RH fluctuations – the RH changes a particular composite object may ultimately endure without irreversible deformation or damage. The Romanesque painted wood ceiling in the church in Zillis, Switzerland offers a spectacular illustration of the severe damage that differing expansion ranges and rates in the constituent materials can cause [5].

An important feature of the measurements described above is that they always relate to equilibrium conditions, i.e. that enough time is allowed for wood to reach a new equilibrium in a new environment. There has been, however, general awareness that the moisture response of materials is a time-dependent phenomenon, and that results obtained at equilibrium conditions may not hold for the dynamically changing environments to which historic wooden objects are often exposed. These may range from diurnal cycles of microclimatic parameters to rapid temperature and humidity fluctuations arising from the use of heating and humidification-dehumidification systems, or the opening and closing of doors and windows, or flow of visitors.

Since this complex response may depend on, among other factors, thickness, density and water vapour permeability of wooden structures and design layers, attempts have been made to monitor historic wooden objects in situ, under the conditions in which they are continually housed. Olstad recorded dimensional changes in the decorated wood in several Norwegian wooden stave churches, both heated and unheated [6]. The dimensional changes showed the same trends as the indoor RH, but no conclusive correlation could be found between dimensional response and development of damage. The discrepancies could be due in part to differences in restraint experienced by the various elements monitored. Richard monitored the dimensional changes that wood veneers and panel paintings might endure when transported by air in microclimate display cases [7]. He showed that paintings transported in aircraft are subjected to variations in temperature, RH and pressure. These give rise to complex dimensional responses that are strongly dependent on the thickness of the wooden element tested. In the transit environment, temperature variations can be large enough that thermal expansion and contraction, which are normally overlooked, can have a significant contribution to the overall changes. It was also observed that the response to temperature change was almost immediate, while the response to RH was fairly slow. Knight measured the dimensional response of pieces of historic furniture in their normal display environment [8]. A lag of about 12 hours between changes in RH and the
corresponding changes in displacement were observed, and the preliminary conclusion was that only slower changes, lasting more than about 24 hours, are measurable.

Measurements of the dynamic dimensional response of wood under display or transit conditions can provide valuable information, but robust, rapid and highly sensitive methods of recording the complex responses are demanded. To date, inductive displacement transducers and foil strain gauges have been applied [6–9]. Both must be firmly fixed to the wood and have been used to monitor simple flat elements such as panels. The moiré technique, applied to record displacements of panel models subjected to cyclical changes in RH, has the advantage of providing non-contact, full-field measurements of out-of-plane displacements such as warp, and offering high displacement sensitivity [10]. But its applicability to in-situ measurements is limited by the need to record, transmit and process a large number of images that can be interpreted only by comparison with a selected initial condition of the object. The use of fibre Bragg grating (FBG) sensors for in-situ monitoring of wood deformation has also been proposed [11]. FBG sensors proved to have high resolution and to be minimally invasive, thanks to their very small dimensions and the option of attaching them reversibly with glue. The authors tested the FBG method on a wooden panel in the laboratory; although the technique is considered to be suitable for continuous monitoring in the field, its use is limited to near-to-planar surfaces and care must be taken in deriving the displacement from a comparison of the two interferometric patterns.

This paper reports the application of triangulation laser displacement sensors to the continuous in-situ monitoring of polychrome wood sculptures. The attraction of these sensors arises from their non-contact nature, rapidity, the precision of measurements and their capacity to operate in the field.

The monitoring has focused on the valuable main altar in the church of Santa Maria Maddalena in Rocca Pietore, Italy, a polychromed and gilded wooden triptych, executed in 1516–1517 by Ruprecht Potsch, a sculptor from Bressanone (Figure 1). The monitoring was part of a broader research programme aimed at developing a novel heating system for churches that would provide a comfortable temperature for the congregation without adversely affecting the works of art [12]. The church, situated at 1143 m above sea level in the Italian Alps, has so far had a heating system based on a forced inflow of hot air. The system operates sporadically, usually once a day, for a short period during services. A detailed study of the internal climate of the church has shown that the system generates rapid temperature and humidity changes [12, 13]. A layering of air temperature causes excessive overheating in the upper part of the church, followed by a rapid change in RH from a high to an exceedingly low level. Due to its size and its position in the church, the main altar is particularly endangered by these fluctuations. Substantial contraction of the wood can be expected when the heating is switched on, followed by a recovery when the heating is off and the people have left.

Principle and features of the triangulation technique

The operating principle of triangulation displacement sensors is well known, and their usefulness widely proven in industrial tests and engineering measurements [14, 15]. It is based on a simple geometrical effect; the sensor projects a beam of light onto an object of interest and the distance between the sensor and the object is calculated by determining where on a detector the reflected light falls. As the object moves closer to, or farther from, the sensor, the image of the
beam spot on the detector changes its position, as shown in Figure 2. The most popular light source is a low-power 670 nm laser diode with a visible red beam.

The laser triangulation technique has several advantages over other optical methods:

- In common with many optical metrology techniques, the modulation of the laser beam intensity and signal detection at a frequency of several kilohertz make the measurement practically insensitive to external light, which is particularly important when monitoring for prolonged periods of time.
- The measurement is absolute, as the distance between the sensor and the object is calculated from the instantaneous value of the signal. This contrasts with other techniques based on the interference of light where the change of distance is derived by comparing fringe patterns. This is a critical point if abrupt changes occur and the sequence of fringe patterns is lost.
- Triangulation laser sensors are small, stable and very robust.
- The laser triangulation technique is fast, as the signal from the sensor can be read at a frequency of up to 20 kHz.
- The technique does not require any computation.

**The measuring system**

The monitoring system met several crucial requirements for the long-term, in-situ measurement of dimensional changes in valuable wooden elements. Triangulation displacement laser sensors LD1605-2 and ILD 1800-2 (MicroEpsilon), both with micrometre accuracy, were used to detect even very small dimensional changes in restrained elements. The laser-to-target distance was about 25 mm, and the range of measurement as wide as ±1 mm, which allows large displacements to be followed without repositioning the sensors.

The sensors were mounted on the altarpiece such that no part of the system touched the valuable decorative parts, thereby practically eliminating any risk of damage. A light and easy-to-handle Bosch mounting system was used, which was securely clamped to the supporting structure of the altarpiece. Two laser sensors were employed to monitor both sides of each wooden element studied (Figure 3). Since three elements were monitored, six sensors were used in total. Small, thin, flat ceramic targets were attached by means of Paraloid B72 to each of the elements monitored and these were positioned perpendicular to the laser beam (Figure 4).

The dimensional change in the element was the difference between the sensor–target distances recorded by these two sensors. Such a monitoring system configuration ensured the insensitivity of the measurement to the relative movement ('wobbling') of the object and sensor in a direction parallel to the laser beam, which always needs to be anticipated when monitoring free-standing objects. In Figure 5 separate plots for the changes in positions of the two targets and their difference are given, reflecting the dimensional change in the object. It is clear that wobbling (of a wooden head in this case) was an important effect and that an experimental configuration that ensures its compensation was needed.

The use of ceramic targets greatly reduced any possible influence of overall movement of the measuring system, or of the elements monitored, in the plane perpendicular to the laser beam. Such movements would introduce a considerable error if the measurements were performed on irregularly shaped carved objects. It should be stressed that only non-contact optical sensors enable the attachment of targets in a way that is harmless to the object. In the case of contact
sensors, a spring return unit produces force of the order of 0.1 N, which would require stable targets to be solidly attached to the object.

The precision of the measuring system is ±2 mm. The wobbling introduces further uncertainty in the measurement, because the ceramic targets are never perfectly parallel to one another. A rough estimation shows that a deviation of one degree from parallel for the position of the ceramic target and wobbling of the sculpture by 0.2 mm introduce an uncertainty of about ±4 mm. Assuming further that wobbling is proportional to the wood response, the relative uncertainty of measurement is 1–10%, depending on the size of the wooden element.

Changes in microclimatic parameters also affect the monitoring system. Thermal expansion of the mounting system is particularly important, as it can exceed the response of the wood. To reduce the influence of thermal expansion, the temperature of the mounting system is measured and a theoretical correction is applied.

To avoid any accidental disturbance, an uninterruptible power supply (UPS) unit was used for the lasers and data acquisition systems. Furthermore, the monitoring system was configured to restart automatically after any accidental interruptions. These precautions are necessary when performing long-term in-situ measurements on an object in an area that is used frequently.

The measurements and data transmission were remotely controlled using a Siemens TC35 Global System Mobile for Communications (GSM) industrial module. The data acquisition system was a CR10X-2M from Campbell SCI. The data were read every five minutes and recorded in the internal memory.

Results and discussion

Three carved elements of differing thickness were monitored: a head – a large, massive element 15.5 cm thick (Figure 6), a drapery – a thin element 13 cm wide and 0.5 cm thick (Figure 3), and a finger – a fine element 4 cm long and 0.5 cm thick (Figure 7). The locations of these elements on the altarpiece are marked in Figure 1. Plots of their dimensional variations in response to a rapid increase in temperature and fall in RH during a single heating episode are compared in Figure 8. The wooden elements responded rapidly to changes in temperature and slowly to changes in RH, as observed by other authors [16].

A massive wooden element (the head) expanded due to temperature increase but no shrinkage due to a fall in RH could be detected; this lack of response was due to the large size of the element. Only the surface began to dry when the RH fell, and it can be estimated that during the one to two hours it was heated, the outer dry layer could become a few millimetres deep [17]. This external zone of dry wood, generated during each heating episode, tends to shrink, but the shrinkage is restricted by the interior, which is still wet and swollen. This creates tension on the outer layer and high stresses are developed, as is evident from the number of cracks running deep into the structure of the wood.

The drapery is a thin object, but its movement is restrained to a considerable extent through its attachment to a massive sculpture. During a heating episode, the drapery experienced a complex dimensional change; it first expanded due to temperature increase but immediately afterwards shrink due to a fall in RH. The finger is a fine object, completely free in its movement. During a heating episode, the finger first expanded, due to the increase in temperature, and then shrank due to the decrease in RH. When results obtained for the drapery and the finger are compared, the much faster and more intense response of this small, unrestricted element is noticeable.
Repeated changes to an element during short heating episodes could exceed the elastic reversible region. This was exemplified by a change in the width of the drapery recorded in the pre-Christmas period, when the church was heated rather more frequently (Figure 9); a cumulative shrinkage of the element was observed.

The measurements also provide a precise record of dimensional changes in the wood due to longer microclimatic fluctuations in the church, as depicted in Figure 10. The dimensional change is always related to the initial state of each of the elements monitored. The response of both small and massive objects can be seen to follow the long-term variations in RH. The longterm erratic movement of the sculptures (wobbling) can be considerable; a maximum of 1.5 mm was recorded for the wooden head during the measuring period between December 2002 and December 2004. Therefore, the uncertainty in the measurement of the longterm dimensional change varies, as illustrated in Figure 10. Obviously, the uncertainty of the measurement of short- or medium-term changes is not affected.

Conclusions

The use of triangulation laser displacement sensors has allowed precise in-situ measurements of short-, medium- and long-term responses of a variety of carved wooden elements to variations in temperature and RH to be made. The effects of these variations are complex because temperature change rapidly affects all the materials in the structure while their response to changes in RH is much slower; the measurements have revealed these various components of the movement. The remote control and data recovery via the GSM transmission system has been effective, and has made monitoring simple to carry out in the field, far from the laboratory. The results of monitoring, which ran from December 2002 to March 2005, were used to assess how different heating systems affect wooden works of art. More broadly, an attempt will be made to use the results from monitoring to establish allowable thresholds for the magnitude and rate of change of temperature and RH that complex painted wooden objects can endure without irreversible deformation or damage.

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Suppliers

Dataloggers and GSM modules: Campbell Scientific Ltd., Campbell Park, 80 Hathern Road, Shepshed, Loughborough LE12 9GX, UK
References

Fig.1. The main altar of the church of Santa Maria Maddalena in Rocca Pietore, Italy. The numbers indicate the positions of wooden elements that were monitored by laser sensors; (1) the Child’s finger, (2) the drapery – a fragment of the Virgin’s robe, and (3) the saint’s head.
Fig. 2. The operating principle of the triangulation displacement sensor.
Fig. 3. Experimental set-up of two laser sensors monitoring each side of a wooden element, a fragment of the Virgin’s robe in this case.
Fig.4. A ceramic target attached to an element and positioned perpendicularly to the laser beam.
Fig. 5. The change in position for the two targets attached to either side of the head, and their difference, reflecting the change in the diameter of the head.
Fig. 6. Experimental set-up to monitor the diameter of the saint’s head. The two ceramic targets are indicated by arrows.
Fig.7. Alignment of two ceramic targets on the Child’s finger.
Fig. 8. Dimensional changes in the three wooden elements of different thickness in response to changes in temperature and RH during one heating episode. Note the different scale for dimensional change in the finger.
Fig. 9. The temperature and RH recorded every five minutes and the change in the width of the drapery in a week with frequent heating episodes in the church.
Fig. 10. The temperature and RH plots smoothed by calculating every five minutes an average of the data points in the two adjacent 24 hour periods and the dimensional changes in the three wooden elements during the period between December 2002 and June 2003. 1 January 2003 was taken as 0 on the time scale.