

Autoreferat
w języku angielskim

Analysis of micro-damage in historic
objects using optical and acoustic
methods

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2. Scientific degrees

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4. As my scientific achievement for habilitation, I indicate a collection of papers under a common title: 'Analysis of micro-damage in historic objects using optical and acoustic methods', as listed below:

- H1. Ł. Lasyk, M. Łukowski, Ł. Bratasz, 'Simple digital speckle pattern interferometer (DSPI) for investigation of art objects', *Optica Applicata*, 41 (3) (2011) 687-700
- H2. L. Krzemień and M. Łukowski, 'Algorithm for automated analysis of surface vibrations using time-averaged digital speckle pattern interferometry', *Applied Optics*, 51 (2012) 5154-5160
- H3. Ł. Lasyk, M. Łukowski, T.M. Olstad, A. Haugen, 'Digital speckle pattern interferometry for the condition surveys of painted wood: Monitoring the altarpiece in the church in Hedalen, Norway', *Journal of Cultural Heritage*, 13S (2012) 102-108
- H4. M. Strojceki, C. Colla, M. Łukowski, E. Gabrielli, 'Kaiser effect in historic timber elements', *European Journal of Wood and Wood Products*, 71 (6) (2013) 787-793
- H5. W. Zawadzki, M. Bartosik, K. Dzierżęga, Ł. Bratasz, M. Łukowski, E. Peacock, 'Application of fiber Bragg gratings for strain measurement in historic textiles and paintings on canvas', *Optica Applicata*, 42 (3) (2012) 503 – 517
- H6. M. Strojceki, M. Łukowski, L. Krzemień, J. Sobczyk, Ł. Bratasz, 'Acoustic emission monitoring of an eighteenth-century wardrobe to support a strategy for indoor climate management', *Studies in Conservation*, 59 (4) (2014) 225 – 232
- H7. Ł. Bratasz, M. Łukowski, A. Klisińska-Kopacz, W. Zawadzki, K. Dzierżęga, M. Bartosik, J. Sobczyk, F. J. Lennard, R. Kozłowski, 'Risk of climate-induced damage in historic textiles', *Strain*, 51 (2015) 78-88, DOI: 10.1111/str.12122
- H8. L. Krzemień, M. Łukowski, A. Kijowska, B. Mierzejewska, 'Combining Digital Speckle Pattern Interferometry with Shearography in a New Instrument to Characterize Surface Delamination in Museum Artefacts', *Journal of Cultural Heritage*, DOI:10.1016/j.culher.2014.10.006, 2014

Declaration of co-authors indicating their contribution to the above papers and estimation of my individual contribution are included in Attachments.

Description of the scientific achievement

Introduction

Analysis of the influence of external conditions on the preservation of art objects during their storage, display and transportation is one of the most important areas of research on the tangible cultural heritage. The practical importance of research supporting preventive conservation was highlighted recently in guidelines published in 2012 by the Group of Organizers of Large-scale Exhibitions (the Bizot Group) bringing together the world's largest museums. The guidelines recommend that the climatic condition control in museums should be based on scientific research, which, in the opinion of the report's authors, would lead to a reduction of energy consumption by air-conditioning systems and would facilitate loaning works of art for exhibitions.

The development of effective preservation methods has been based mainly on the analysis of interaction between various materials constituting a work of art in changing environmental conditions. This applies particularly to objects made of a material susceptible to water vapour. Measuring of mechanical and rheological properties, dynamics of water vapour sorption and moisture-related dimensional changes of hygroscopic materials such as wood, decorative layers, canvas, leather, etc. leads to the determination of strain and stress causing irreversible deformation or cracking of the whole objects or of their individual layers.

A fundamental, practical problem of the described approach, lays in the accuracy of determination of the material properties. Usually, it is not possible to sample museum objects, and even if curators of collections are ready to provide such samples, their sizes are too small for most of the required tests. Therefore, usually, measurements of the physical properties are carried out on samples simulating historical materials (similar composition and manufacture technology) subjected to processes of accelerated aging at elevated temperature and humidity. As a result, the correctness of recommendations concerning exhibition and storage conditions, based on the material research, may be questioned, or even contradicted - in case of unique or particularly vulnerable art objects.

To avoid this, existing in the field of heritage science, problem, the research on direct monitoring of micro-damage occurring in art objects during their exposition in various environmental conditions has been developing rapidly. The great advantage of this approach is the ability to obtain information about the changes in the state of preservation of a real historic object, if only the measurement is precise, repeatable and resistant to the environmental noise. Monitoring systems act as "early warning systems" informing collection curators about environmental events causing micro-damage to the objects. Obviously, the results can be used to verify the correctness of models describing object deformation and damage on the basis of the measured material properties.

Research aims

Research that I have carried out for the past eight years aimed at developing acoustic and interferometric methods for direct measurement of micro-damage in historic objects. Basing on these methods, I have also sought to develop means of objectively assessing risks associated with the storage or display of monitored objects in particular environmental conditions.

The biggest challenge, in comparison to engineering applications where such systems are widely used, is long monitoring time and need to eliminate influence of the environmental noise. Further, the methods used must take into account the huge variety of the materials undergoing damage processes. Hygroscopic materials used by artists equilibrate with ambient conditions with varying dynamics and are characterized by different temperature and humidity coefficients of expansion. Therefore, during the measurements, it must be taken into account that, depending on the structure of historic objects, micro-damage can appear both on the surface and in the bulk of the examined objects. Moreover, some of the artistic materials cyclically pass the ductile-to-brittle transition at temperatures and humidities typical of the museum conditions. This further increases the risk of damage.

Another, very important issue in the field of art object preservation, is the requirement of simplicity of the measurements and their interpretation as well as clear communication of results to the museum and conservation community. Since the purpose of my work was not only to understand the damage processes but also to introduce the elaborated monitoring methods to the conservation practice, the developed tools, by definition, have been expected to operate automatically and provide results in a form which is easy to interpret.

Given the above requirements, I decided to develop three research methods: speckle interferometry, acoustic emission and fibre Bragg grating sensors. The first two methods have led to the development of systems for measuring formation of cracks in the decorative layers and wood substrate in objects such as panel paintings and historic furniture. In turn, the fibre sensors have enabled continuous measurements of deformation of historic textiles and canvas supports of paintings.

A series of eight publications is an illustration of the main achievements of my research. Below I present results of the research divided into three sections dealing with the three monitoring techniques applied to diagnose the risks specific to certain categories of materials and types of historic objects.

Speckle Interferometry

Digital Speckle Pattern Interferometry (DSPI) is a kind of holographic interferometry based on the analysis of laser light scattered on the optically rough surface. This technique is commonly used to analyse sub-micrometre deformations and displacements as well as vibrations of objects. It enables a non-contact measurement of the surface deformation in real time with high speed and precision. Over the last twenty years, a number of experimental techniques based on speckle interferometry have been elaborated. Continuous or pulsed laser light sources, different design of optical systems as well as various methods of recorded images analysis have been applied. DSPI has been used in academic and industrial research and quality control of construction elements (e.g. in the aerospace and automotive industries).

DSPI began to be used to analyse the state of preservation of works of art in the 1980s as an alternative to the holographic interferometry which required laboratory conditions. High efficiency in detecting damage areas on the surface of panel paintings, resistance to the environmental noise and objective nature of the measurement resulted in the application of the technique also to assess damage of wall paintings and mosaics. However, high price of measuring systems as well as complexity of the measurements and interpretation of the results have been for a long time a serious barrier in the wide use of interferometric methods in the field of cultural heritage preservation.

The situation has changed radically during the last ten years. Cost of measuring systems is no longer a barrier to their use – price reduction of the optical components is particularly evident in the case of diode pumped single-mode CW lasers. Also, a huge increase in computing power of personal computers allows the complex calculations required for the analysis of the measurement results to be done almost in a real time. The biggest challenge remains a complex nature of the measurement and difficulty in a quantitative interpretation of interferometric images recorded during the test. The latter problem is particularly important for the conservation and museum community, because the purpose of the analysis of the preservation state of the objects is not only the detection of surface defects but also, and perhaps above all, a quantitative assessment of the extent of damage and the risk of its propagation.

Therefore, the main objective of my research was to develop a DSPI method which would effectively facilitate work of conservators, allowing a quantitative assessment of the surface micro- damage; methods that would be easy to use, and allow for an intuitive interpretation of the results.

My studies were conducted using speckle interferometers designed and built by myself – such approach gave me freedom to test various components of the optical system and to construct devices of the size and shape that could be adapted to the geometry of the

tested objects. At a very early stage of the work, I decided to use the measuring technique based on the registration of continuous light. Interferometers employing pulsed lasers allow, by using the stroboscopic techniques, for an easier interpretation of the results in the case of analysing vibrating surfaces, but require a higher power of the laser light and a precise synchronization between times of light exposure and image registration. This would require an additional calibration of the system prior to the measurement. The primary advantage of the developed measuring system was its flexibility. In the simplest version, it worked as a digital image correlation (DIC) optical system, after an extension with the additional reference beam path, it could be used for the analysis of the spatial distribution of the surface response to changes of temperature, and finally after employing a phase shifter in the reference beam path, the system could allow a quantitative analysis of surface vibrations.

The operation of the simplest measuring system (DIC) consists of registering and subtracting images, one from another, in real time, of the surface illuminated with light of a single mode continuous work laser during heating or cooling of the surface. The change in temperature causes deformation of the surface and the magnitude of this deformation depends on the temperature of the analysed area. The larger the temperature differences between the consecutive registrations, the greater the change in the light intensity in the recorded interferograms. Therefore, digital subtraction of the recorded images allows heterogeneity in the distribution of surface temperature to be detected, which is related to structural defects: cracks, splitting or delamination of decorative layers. After adding the reference beam to the measuring system (ground glass was used to create the speckle reference beam to maximally simplify the construction of the optical interferometer), the measurement is performed in the same way, but the obtained results have a form of the distribution of the interferometric fringes. These fringes become clustered in areas where local deformations, associated with the surface temperature heterogeneity, are present. The method is highly sensitive, can precisely point out places where heterogeneities in response of the material to stimulus, such as an increase or decrease of temperature, are present. However, the result of measurement is not unequivocal. Creation of the interferometric fringes clustering during the heating of the surface may result from local differences in heat capacity or thermal conductivity of the object caused by different thickness or non-uniformity of the substrate (e.g. knots in the wood constituting the substrate). To distinguish a surface damage (delamination of the decorative layer from the substrate or its splitting) from the heterogeneity of the object structure, a method based on inducing vibrations of the surface using sound wave was applied. In this method, the sound wave emitted from a loudspeaker is the source of the force inducing surface vibrations. During the measurement, the sound frequency is tuned to be in a resonance with the delaminated part of the decorative layer. Registration of vibrating parts of the surface allows not only the position of damage to be indicated unambiguously, but also allows the size of the defect and the resonant frequency at which its vibration occurs to be

specified. Additionally, the application of phase unwrapping algorithms utilizing a controlled delay between the reference and object beams (e.g. four-frame algorithm) allows the spatial distribution of the surface vibration amplitude to be determined. This last result, however, requires stable measuring conditions - registration of at least eight images with a well-defined phase difference between the object and reference beams.

As a result of the conducted research, it was possible to construct a speckle interferometer capable of analysing the painting surface preservation state as well as to develop and optimize the measuring procedure. The first step of this procedure is an analysis of the interferograms obtained when heating the surface. Then, in places selected on the basis of thermally induced DSPI, the sound induced procedure is applied to confirm the existence of delamination of a paint layer and characterize the damage. Three-level damage characteristic is provided. Firstly, it is possible to determine the size of vibrating area, secondly the spatial distribution of the vibration amplitude, and finally, the fundamental and higher harmonics of the resonant frequency of vibration. The exact description of the measurement system and applied procedures is presented in publication H1.

The results obtained for the model objects in the laboratory were the basis for a research work performed in a historic church in Hedalen, Norway. The main objective of the study was to assess the impact of a heating system operating in the church on the damage progress in the medieval polychrome altarpiece located in the interior. The DSPI measurements were performed on fragments of the altarpiece selected by conservators from the Norwegian Institute for Cultural Heritage Research (NIKU) - the selection criteria of the analysed surfaces were their representativeness for the polychromy in the church and access for the measuring equipment. Two surveys were conducted at an interval of one year to trace sub-micrometric changes in the preservation state of the selected surfaces. As a result, it was possible to describe precisely the preservation state of the altarpiece's fragments and demonstrate that changes of relative humidity caused by operation of the heating system had a very small (but measurable) impact on damage progress in the decorative layer. The obtained results had practical implications. NIKU conservators decided to leave valuable and sensitive objects in the church, even though they initially planned to transfer them to a museum due to the bad climatic conditions in the church. The results of the measurements are presented in publication H3.

Measuring campaigns carried out in the interior of a historic church made me realize that DSPI can effectively support management of object storage conditions by providing information that is relevant and difficult to obtain in any other way. However, two important and interrelated problems remained to be solved. The first was difficulty with making measurements in presence of a high environmental noise. The detection of surface defects was possible in a noisy environment, but the determination of the spatial distribution of the vibration amplitude, requiring a series of measurements carried out with a controlled phase difference between the laser beams, was not possible due to an insufficient mechanical stability of the measuring system. The second problem

concerned the issue of communication. The results presented in the form of interferometric fringes were difficult to understand for conservators, and the procedures allowing transformation of interferometric images into maps showing the spatial distribution of vibration were only partially automated - in the existing algorithms for spatial phase unwrapping one needed to spot the position of the first maximum of the Bessel function describing the dependence of the light intensity on the amplitude of the vibrations as well as manually mark the boundaries of vibrating areas. My further research was focused on solving these two problems.

To automate the method of measurement and data analysis, I decided to try a completely new approach based on registration of the interferograms while gradually increasing the intensity of sound inducing surface vibrations. The procedure consists in performing a series of measurements with a controlled phase difference between the laser beams for a progressively increasing sound amplitude of the pre-selected frequency. As a result, a series of interferograms showing the distribution of the amplitude of surface vibration for increasing amplitude of these vibrations is obtained. The intensity of the signal at each point of the recorded interferogram is given by a Bessel function of a first kind whose argument is the amplitude of the surface vibration. If, in addition, we assume that the amplitude of vibration is proportional to the emitted sound intensity, we can fit the Bessel function to the recorded signal at each point of images registered for increasing pressure of the acoustic wave emitted by the loudspeaker. The idea of signal analysis leading to determination of the spatial distribution of the surface vibration amplitude is presented in Fig. 1.

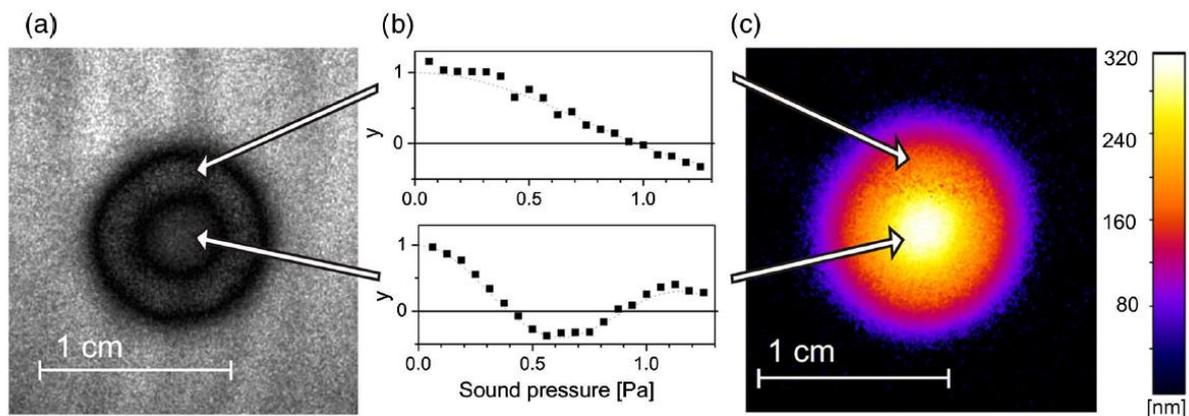


Fig. 1. Analysis of sound-induced vibrations of a paint layer delaminated from a wooden support (Specimen 1); (a) an interferogram obtained for a surface vibrating with different amplitudes; (b) results of fitting the function to chosen pixels marked in (a); (c) reconstruction of vibration amplitude.

A major drawback of this calculation procedure is its time-consuming nature. The program for data analysis works fully automatically but requires a nonlinear function to be numerically fitted to a set of data for all points of the registered image. For the camera with 6.6 million points, used in the experiments, several hours of computation on a standard personal computer was required. Such a delay between recording of the

images and obtaining the results is unacceptable in the case of measurements of artworks - where, due to limited access to objects, optimization of a measurement must be done in real time on the basis of the obtained results.

Speeding up the calculation was therefore a key issue. Since finding the fitting parameters is the most important part of the procedure for the determination of the surface vibration amplitude, it was necessary to simplify the form of the fitting function. This was possible by transforming the measured data. A Hilbert transformation, which can be treated as a $\pi/2$ phase-shift operation on any semi-periodic function (so also the Bessel function), was used for this purpose. Arctan of the quotient of signal and its Hilbert transform is a linear function, and fitting such function can be well optimized numerically. Using the Hilbert transform in the calculation procedure allowed this procedure to be accelerated several times so the measurement results were obtained after only a few minutes. This was at the expense of accuracy (a mathematical phase-shift operation is only approximate), but the differences in obtained vibrations amplitude for the results of the direct fitting of the Bessel function or fitting a linear function to the data after the Hilbert transform did not exceed 10% in typical cases. From the point of view of an effective use of interferometry in historic buildings, the benefit from speeding up the measurements compensates well the inaccuracy of the measurement - the more so that, if necessary, all calculations can be repeated using the method of direct fitting of the Bessel function after the survey of a historic object is completed.

Summarizing, the work on the optimization of the measurement procedure allowed me to construct an interferometer that is easy to use (once the resonant frequency is found, the entire measuring sequence can be done automatically) and provides a fully automatic data analysis. Thanks to the use of approximate methods of signal processing, the result is obtained after a few minutes, allowing precise planning and effective conduction of the measuring sessions. It is worth noting that the amplitude of the surface vibration is determined at each point independently, therefore, the results are highly resistant to error propagation; it is easy to introduce an error control (e.g. by controlling the quality of the linear function fit) and identify erroneous calculation results. The applied method of measurement and the data analysis have been presented in detail in work H2, and the analysis of the accuracy of the data analysis in publication 6 listed in refereed conference proceedings (the publication is not included in the list of publications constituting the habilitation achievement).

The last, and perhaps the biggest, practical problem during the measurements in out-of-lab conditions are uncontrolled vibrations of the measuring system with respect to the analysed surface. A speckle interferometer requires the use of a reference light beam to reconstruct the spatial distribution of the vibration amplitude. This light beam is created inside the interferometer, therefore, even small vibrations of the measuring system with respect to the analysed surface result in uncontrolled, abrupt phase changes and disrupt

the measuring procedure. The problem can be partially solved by repeating measurements many times for the same amplitude and frequency of sound or by filtering erroneous results at the stage of the Bessel function fitting. But in some cases, the environmental noise is so high that the measurement cannot be successfully performed. Such a situation occurred during work on wall paintings from the Faras collection carried out jointly with the conservators from the National Museum in Warsaw. The aim of the project was to analyse the preservation state of the paintings in order to assess the stability of the surface layer of selected fragments of the frescoes, quantitatively describe splitting and delamination of the surface layers and evaluate risks associated with the scheduled display of these objects in the new gallery. The task proved to be very difficult due to large size of the paintings and resulting impossibility to firmly connect the measuring system to the investigated surface. The failure to reduce the mutual vibrations of the object and the interferometer prompted me to look for a different solution of the problem. I decided to expand the measuring system by adding a shearographic interferometer DSSPI (Digital Speckle Shearing Pattern Interferometer) to the existing optical setup. In the DSSPI system, light reflected from the surface is divided inside a Michelson type interferometer into two beams which create a double image of the analysed surface on a CCD matrix. As a result, a movement of the object and the measuring system changes both the object and the reference beams in the same way, and so does not cause any decoherence of the registered interference pattern.

It should be emphasized that shearographic system in the constructed device operates differently than in other systems of the similar type, in which the directional derivative of surface deformation is analysed. Here, the lateral shift between the interfering light beams is adjusted in such a way that the light scattered from vibrating and non-vibrating areas coincides. This allows the signal analysis to be performed using the same algorithm which is used in case of DSPI. An obvious consequence of applying this approach is that two overlapping images are recorded. It may potentially result in difficulties in data interpretation when damaged areas are small but numerous, or, conversely, larger than the image recorded. To avoid these problems, the shearing interferometer was combined with a digital speckle-pattern interferometer within one measuring device and the measuring protocol, providing unambiguous interpretation of the results (DSPI) and insensitivity to vibration (DSSPI), was elaborated. The measuring system and its photograph are shown in Fig. 2.

The double-step analysis is performed for each investigated area. In the first step, sound-induced DSPI is used to document defects of the surface, that is, to determine the size and resonant frequencies for each existing delaminated fragment. In the second step, sound-induced DSSPI is used to obtain the spatial distribution of the amplitude of vibration for the delaminated areas at selected frequencies. The results of such double-step analysis allows the response of the surface to vibrations induced by the loudspeaker to be described precisely, and consequently provides very precise information about the physical integrity of the analysed areas. The result is a full

characterization of surface defects obtained with help of an automated calculation procedure. The described method gives reliable results even in presence of a high level of the environmental noise. Detail presentation of the measuring system as well as the detection and analysis procedure is given in publication H8, where also results obtained for the Faras collection are presented.

In conclusion, the speckle interferometry method proved to be very effective in the analysis of the preservation state of art object surfaces. The developed measuring systems and procedures for signal recording and data analysis enable changes of the surface to be evaluated with a high precision. This in turn, allows influence of storage and display conditions on the object preservation state to be assessed in a relatively short time interval (in typical measuring campaigns this time was one year).

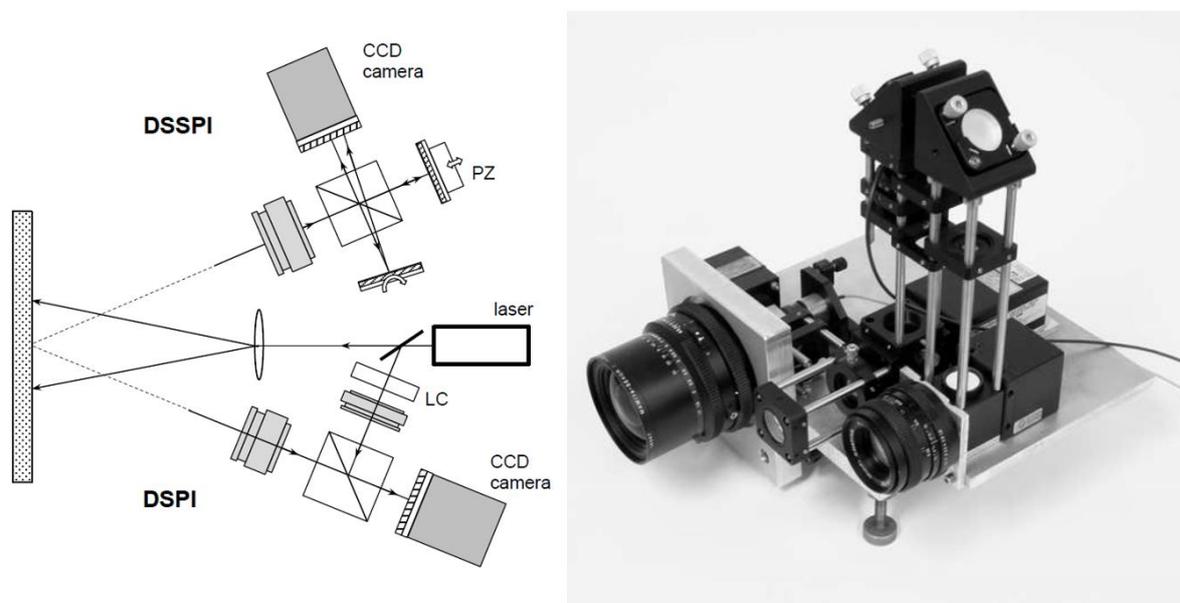


Fig. 2. Layout of the experimental setup used for the analysis of sound-induced surface vibrations. PZ: mirror on a piezoelectric crystal; LC: liquid crystal phase retarder – both used for introducing phase retardation between object and reference beams.

Acoustic Emission

Parallel to the work on characterizing surfaces using the interferometric techniques, I continued, research on the application of acoustic emission method, developed earlier at the ICSC, to evaluate the influence of climatic conditions on historic objects. The term “acoustic emission” is used to describe a monitoring technique but also energy which is released in a form of an acoustic wave due to micro-displacements in a structure undergoing deformation. The energy passes through the material as ultrasound and sound waves, and is detected at the surface using a piezoelectric transducer which converts the surface vibration to an electrical signal. Measurement of the acoustic

emission allows a correlation between the damage and the external conditions in the vicinity of the object to be determined. Importantly, the acoustic emission enables recording micro-damage in real time in the bulk of the material making this technique complementary to the interferometric methodology described above, which allows only the surface of the object to be characterized at a certain point in time.

For more than 50 years, the acoustic emission method has been successfully applied in civil engineering and material science to monitor the safety of buildings and the load/fatigue resistance of their critical components. In most materials of crystalline structure (predominantly metals), acoustic emission is not observed during the reloading of a structure until the stress exceeds its previous value. This ability to “memorize” the highest stress level already experienced was termed the Kaiser effect. Studying the Kaiser effect in organic materials, such as wood, is more complicated due to by their marked visco-elastic properties which lead to stress relaxation. The previously published works on the acoustic emission in new, but seasoned wood show that the Kaiser effect disappears after just two weeks after mechanical testing (wherein both tensile and torsion tests were performed). It should be noted that the total lack of the Kaiser effect (that is, to put it more vividly, the "lack of memory" of the stresses exerted on the object) means that each load cycle would cause the same damage to the object. This statement is in a clear contradiction to the universally accepted acclimatization concept according to which the risk of physical damage is very small as long as temperature and humidity conditions in the vicinity of the object, are in the range of their past variability.

Therefore, I considered important to examine the Kaiser effect in historic wood, of which furniture, panel painting supports and construction elements of buildings are made. In cooperation with partners from Bologna University, the acoustic emission method was used for monitoring of micro-fracturing in the 150-year old timber beams recovered from the roof of the Prosperi-Sacrati palace in Ferrara. The experiment consisted of cyclic 4-point bending tests with increasing load in subsequent cycles. The acoustic emission was recorded using the measuring system constructed in ICSC, with help of broadband, multi-resonant piezoelectric sensors. In order to assess the degree of relaxation of the material and its effect on the measured signal, the whole series of experiments were repeated after a year on the same beams using the same loading scheme.

The experiment demonstrated a short-term Kaiser effect that occurs in the tested samples (as in the samples from new, but seasoned wood). The measurements repeated after a year revealed a long-term persistence of the Kaiser effect (which was not observed for samples made of new wood). An experimental verification of the Kaiser effect in old wood has opened a new perspective for determination of load histories of wooden works of art and constructions, which is essential for assessing the risk of their

mechanical damage. The applied methodology and detailed experimental results are presented in publication H4.

Measurements of cyclically loaded structural components made of historic wood once again confirmed the clear correlation between the deformation resulting from an external force exerted on the material and energy of the recorded acoustic emission signals. This result encouraged me to undertake a long-term measurements of the micro-damage progress in wooden works of art caused by stresses resulting from microclimate instability. These measurements required development of a detection system capable of performing monitoring in the presence of a high level of the environmental noise. In museum conditions, inside an air-conditioned building, a very low level of signal originating from micro-fracturing of material in comparison to the background noise is expected. It was, therefore, necessary to use highly-effective filtering of any signals resulting from processes different than the fracturing of monitored object.

In the acoustic emission, a frequency filtering of measured signals is a common method to reduce influence of the environmental noise. Laboratory tests showed that it was not possible to find a single characteristic frequency of the acoustic emission signals correlated with the micro-fracturing of wood. Signals were attenuated when passing through the material, their frequency was also disturbed by characteristics of the utilized detectors and amplifying electronics. Therefore, it was decided to use a high-pass filtering just to cut off the low-frequency background noise rather than measure signals in a narrow, well-defined frequency window. The measuring schemes based on various AE detectors (wide-band: flat and multi-resonant and also narrow-band) as well as different frequency thresholds were tested. The results showed that the frequency filtering significantly improved the signal-to-noise ratio and allowed most of the unwanted signals obscuring the monitoring results to be discarded. However, the approach is not sufficient to perform a quantitative analysis of the micro-damage progress of art objects in the museum conditions. This is because the signals generated by staff and visitors or electronic noise, though rare, are of comparable or higher energy than the signals associated with the micro-fracturing of the monitored object structure.

To solve this problem, I proposed a system based on two wideband differential acoustic emission sensors working in an anti-correlation mode. Two identical AE sensors were installed at such a distance that events recorded by one sensor were out of the range of the other. All the signals registered in the same millisecond by both sensors were discarded from analysis as not originating from micro-cracking of the material. So finally, combination of the anti-correlation scheme with high-pass signal filtering allowed signals related to micro-cracking induced by environmental instability in object's vicinity to be measured effectively.

The developed measuring system was used, for the first time, to monitor an eighteenth-century wardrobe displayed in the Gallery of Decorative Art in the National Museum in Krakow. This object was selected by the conservators as representative of bulky furniture displayed in the galleries, but was also considered as particularly vulnerable to climate-induced damage. The acoustic emission sensors were located close to the tips of existing cracks - the most vulnerable places where stress concentrates. The monitoring was carried out for two years. Analysis of the results consisted in the determination of temporal correlation between the level of measured acoustic emission and relative humidity falls that lead to shrinkage and cracking of wooden furniture elements.

Analysis of the monitoring results started with establishing time correlation between recorded acoustic emission signals and climatic variations inducing them. A response time of the object to changing climatic conditions in its vicinity depends on the moisture diffusion coefficient as well as size and geometry of the object. The procedure of risk evaluation consisted in choosing a time window corresponding to the response time of the analysed element of the object, and calculating a simple moving average of relative humidity (RH) for this time period. In case of the analysed wardrobe, the time window was one week. Then a corresponding value of the RH average was attributed to each AE signal. The last step in the analysis was determining the correlation between number of falls of the RH average and energy of acoustic emission signals recorded during these falls.

The results of the acoustic emission monitoring and the cumulative crack propagation per year which occurred as a result of drops of one-week RH average not going below the RH_{min} level in the entire monitoring period is presented in Fig. 3. Detailed description of the calculations and calibration procedure, allowing the damage to be determined on the basis of the measured acoustic emission energy, is presented in publication H6.

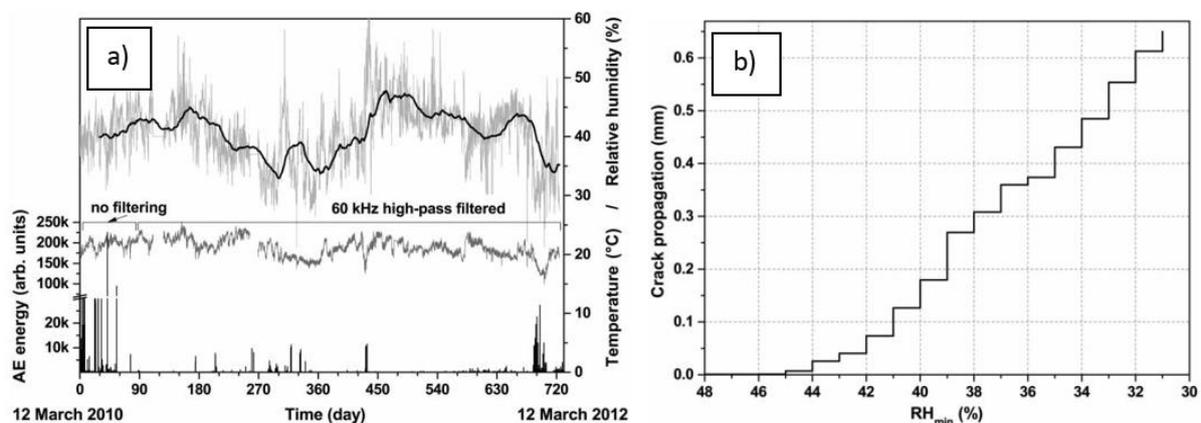


Fig. 3. The results of two years of monitoring of a wardrobe in the National Museum in Krakow: a) temperature, relative humidity and acoustic emission (presented as vertical bars), b) cumulative crack propagation per year.

The presented results were obtained for a particular object displayed in specific microclimatic conditions. This result is however of a fundamental importance for determining the risk associated with impacts of uncontrolled falls in relative humidity on wooden works of arts. If we assume that the analysed piece of furniture is a good representative of a whole collection (or is its representative most susceptible to damage), basing on Fig. 3, we can determine the expected increase of damage in relation to the humidity control strategy in the gallery. This is extremely important for planning and installing new air conditioning systems in museums as well as optimizing climate control algorithms for the existing ones.

Success in using acoustic emission to direct tracing damage development in wooden works of art results from high precision and non-invasive nature of the measurement. Currently, works on further modification of the system are underway. They consist in its miniaturization, utilization of new sensors of high sensitivity and uniform frequency characteristics and use of the internet connection to control the data acquisition process.

Fibre Bragg grating sensors

Analysis of applicability of fibre Bragg grating sensors to measuring changes in textile objects (including paintings on canvas) was a natural, next step in searching for systems capable of monitoring humidity induced damage in hygroscopic materials. Textiles constitute a very important and large part of museum collections. In the opinion of conservators and collection curators, changes in ambient temperature and relative humidity causing the swelling-shrinkage cycles in fibres can damage objects. Therefore, museum conservation standards and guidelines recommend a strict control of temperature and humidity in premises where the textile objects are stored.

Long-term monitoring of structural changes of textile objects induced by microclimatic fluctuations is a difficult task. Objects are too unstable geometrically for measuring their preservation state using the interferometric methods. On the other hand, textiles have too loose structure and too high sound attenuation coefficient to monitor damage progress using the acoustic techniques. In contrast, an optical fibre with incorporated Bragg grating seems to be a good solution for monitoring the textile deformation. The design of the sensor is very simple: on a few millimetres length of a fibre a periodic change in the refractive index of the core is produced by irradiating the fibre core with a spatially modulated intense UV laser beam. This structure acts as a diffraction grating i.e. reflects electromagnetic waves in a narrow band with full width at half maximum smaller than 1 nm. The reflected wavelength depends on the Bragg grating constant and therefore is proportional to elongation of this fragment of a fibre where the grid is located. As a result, it is possible to measure local dimensional changes of a fibre bonded with the monitored textile. What is important, many Bragg gratings with different constants can be created in various parts of one optical fibre. They perform as

independent sensors providing information about local deformation of the fibre. The measuring system needs only one superluminescent diode to operate. What is important, the diode does not need to be stabilized because the results depend only on the change in the wavelength of the reflected light (proportional to the grid constant) but not on the light intensity.

Development of an effective strain sensor based on fibre Bragg gratings required selection of an appropriate materials (the type of the fibre core and the coating), choosing a method of connecting it with the tested canvas and proper calibration of the measuring system.

Since the long-term stability of the sensor is its most important feature, it was decided to use, in the measuring system, a single-mode fibre with a quartz core transmitting light of wavelength of about 1550 nm. Two types of fibre coatings were tested: acrylate and made of organic modulated ceramic (ORMOCER), which is a hybrid polymer material synthesized in the sol-gel process. The mechanical tests showed that the ceramic coating provided a better strain transfer to the fibre core and to a much lesser extent crept under a constant force. A comparison of the two sensors is presented in Fig. 4.

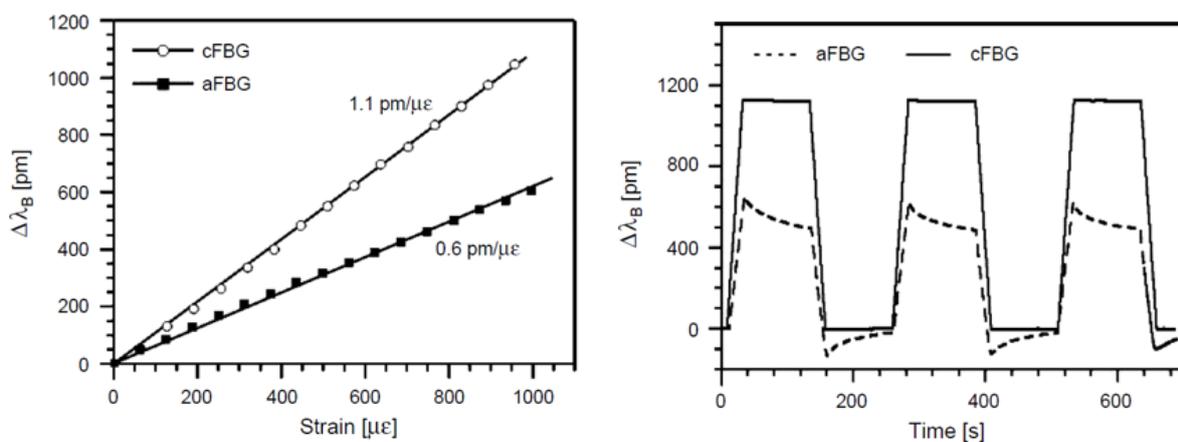


Fig. 4. Comparison of the characteristics of sensors with acrylate (aFBG) and ceramic (cFBG) coatings. Left figure: strain transfer from coating to core of the fibre; right figure: response of sensor to strain cycling

The biggest difficulty during the sensor construction was a high rigidity of both fibres (about 31.5 GPa) resulting from the properties of their cores made of quartz. I realized that it could create a serious problem when monitoring the deformation of delicate textiles, because the installed sensor would significantly reduce the deformation of the monitored material. This effect could be minimized by using a sufficiently big mounting clamps - magnetic holders with a width of 1 to 10 cm were tested. It should be born in mind, however, that although the wide clamps minimize the impact of the fibre on the textile, they limit the local nature of the measurement.

Despite these limitations, it was shown that the optical fibre sensor can be calibrated in a function of the width of the mounting clamps making possible monitoring of textile deformation in laboratory as well as in gallery conditions. Long-term monitoring required use of a reference sensor (not connected to the monitored object), which records deformation of the fibre core caused by dimensional changes of the fibre coating induced by humidity and ambient temperature variations. Description of the fibre optic sensor design, calibration procedures and results of test measurements are given in publication H5. In this publication, an application of the Bragg grating sensor for measurements of strain in paintings on canvas during transportation is also described. The canvas was stretched on a wooden stretcher and pre-sized with an acrylic preparatory layer in which an optical fibre was incorporated. The strain of the canvas was measured at different distances from the painting centre. A comparison of in-plane deformations measured directly by the fibre sensor and the deformations calculated from the out-of-plane distortions measured by a laser triangular sensor shows that both measurements are in a good agreement and proves that, in the analysed case, the fibre sensor provided accurate and unambiguous results.

Fibre sensors proved to be very useful in understanding the influence of unstable microclimatic conditions on historic textiles. This problem was systematically studied within the frame of the project supported by the Financial Mechanism of the European Economic Area (EEA). For selected historic textiles (wool and silk) as well as modern ones, sorption of water vapour, the associated dimensional response, and tensile mechanical properties, including a susceptibility to fatigue-induced processes at large number of tensioning cycles, were measured. The measurements were designed to evaluate two potentially destructive processes: stress building as a result of shrinkage of a textile restrained in its dimensional response and the fretting fatigue when yarns move with friction against one another on cyclic extension and contraction. In both cases, the risk of damage depends critically on the amplitude of strain to which the textile is subjected during consecutive deformation cycles. Determination of climate-induced strain amplitudes was indeed possible owing to a yearly monitoring of a 17th century Flemish wool tapestry from the collection of the National Museum in Krakow performed with the use of the fibre Bragg grating sensors. The results showed a significantly non-linear relationship between the measured strains and relative humidity changes that induced them (Fig. 5). The overall recorded expansion of the tapestry did not exceed 0.05% during the year – which together with results of the fatigue tests – allow the risk of climate induced damage to this kind of objects to be assessed as very low. The results show clearly that humidity fluctuations in the gallery do not pose a threat of physical damage to textile objects unless they are extremely delicate or already severely damaged. All results of this study are presented in publication H7.

The use of the fibre optic sensors contributed to assessing risk related to storage of historic textiles in unstable climatic conditions, which is a very important preventive conservation problem. It also opened up a perspective of constructing a sensor capable

of monitoring local deformation of historic textiles for a long period of time in a non-invasive way. The necessary condition for constructing such sensor is, however, solving a purely technological problem of introducing a flexible material for the construction of the fibre core. The material in which a stable Bragg grating will persist for long time despite material's relatively small stiffness.

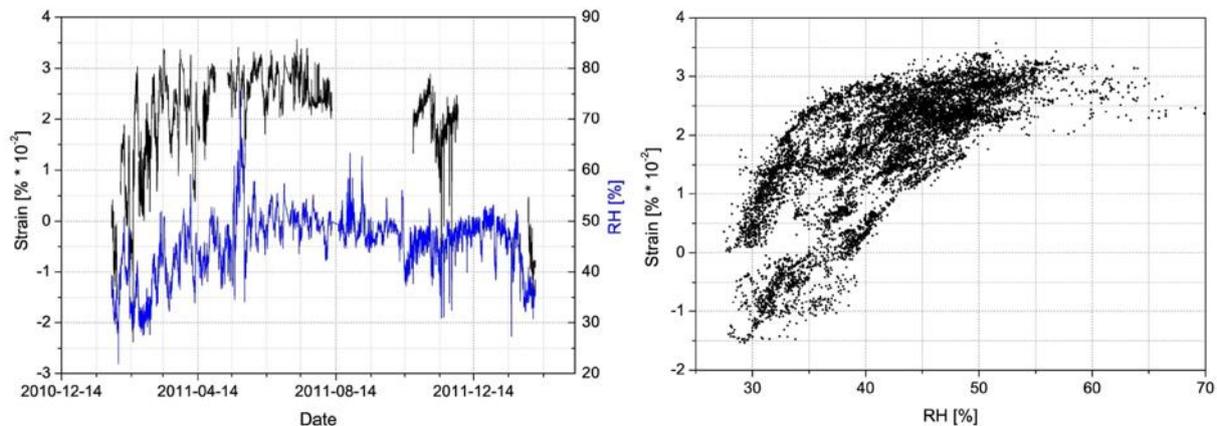


Fig. 5. Results of yearly monitoring of a Flemish wool tapestry using a fibre Bragg sensor. On the left: RH and strain along the weft yarns of the tapestry measured in the gallery; on the right: relationship between the measured strain and RH

Summary

As a result of the research carried out, systems measuring deformations and micro-damage of art objects as well as algorithms to interpret results obtained with their help were elaborated. The work on such measuring systems requires understanding of the specific problems related to the preservation of art objects and the specific requirements with which these detection systems must comply. The success depends in this case mainly on the creative use of the existing technology and adaptation or development of methods required in the field of art object preservation. The developed monitoring systems have been applied and tested under several measuring programmes in museums and historic buildings. These programmes have helped to better understand and quantitatively describe the impact of changing environmental conditions on the preservation state of monitored art objects. They also helped to establish the acceptable ranges of temperature and humidity variations in the vicinity of objects, becoming the basis for the development of new strategies for climate control, for example in the Museum of Princes Czartoryski, the National Museum in Krakow, and the Victoria and Albert Museum in London.

5. Other scientific achievements

Research work before obtaining a doctoral degree

I graduated in physics from the Department of Mathematics, Physics and Computer Science, Jagiellonian University, Krakow. My master thesis was prepared under the supervision of professor Karol Musioł. The experimental work, providing the basis of my thesis, was focused on testing argon arc plasma parameters using two diagnostics methods. The first, the optical emission method, consisted of measuring intensities of spectral lines emitted from the plasma source whereas the second was based on a nonlinear phenomenon of degenerate four-wave mixing inside the plasma source under the influence of a strong laser field. The results confirmed that both methods can be used for plasma diagnosis. The experiment revealed limitations of the two approaches, therefore, a possibility to use them in a complementary manner was suggested. The results were presented in my Master thesis: "Atomic spectroscopy using four wave mixing", were also shown at the Second Polish-French Seminar in Krakow and won an award for "The quality of experimental or theoretical research on plasma or its applications done by a young scientist" from the Franco-Polish Committee of Plasma Physics.

Between 2000 and 2003, I did my PhD studies in the Department of Mathematics, Physics and Computer Science, Jagiellonian University, Krakow. Dr. Jaroslaw Koperski was the academic supervisor of my doctoral dissertation. My research was focused on the characterization of electronic states of van der Waals molecules (CdKr and Cd_2). The method was a laser spectroscopy of complexes in supersonic beams. A tunable dye laser pumped by Nd: YAG was used as a light source in the experiments.

The results were analysed using classical approximations (Birge-Sponer, LeRoy Berstein) and numerical, perturbation methods for the calculations of interatomic potentials. A two-step procedure combining both approaches allowed the double-well potential energy curve of a cadmium – krypton molecule in the $B1(5^3P_1)$ excited state to be characterized on the basis of relatively limited experimental data. The perturbation analysis starting from analytical representations of the molecular potential energy curves yielded also very good results in case of analysis of the 0_{u}^+ (5^1P_1) state in a Cd_2 molecule. The obtained results proved that the elaborated procedure could be regarded as an integral method of molecular electronic spectra analysis. Subsequent research projects carried out in the Molecular Laser Spectroscopy Group at the Department of Atomic Optics confirmed the usefulness of perturbation numerical calculations in supporting classical methods of the vibrational spectra analysis. This combination of analytical methods was used for the characterization of different electronic states of der Waals molecules. The results were presented in several scientific publications.

An experimentally determined repulsive branch of the $X0\frac{1}{2} (5^1S_0)$ electronic state in the Cd_2 molecule was a completely new result difficult to describe within an existing theory of van der Waals bonding. The obtained shape of the molecular potential curve finally confirmed the hypothesis about the contribution of covalent binding in the ground state of the Cd_2 molecule. The results were published in international journals and presented during national and international conferences. My oral presentation of a two-step method for the analysis of molecular electronic spectra, won an award at the conference in Jurata, in 2002 (The 2nd prize for the "Young Lecturer" of a Short Communication on the IV-th Workshop On Atomic, Molecular Physics and Optics, Jurata, 19-21 September 2002). My PhD dissertation: "Spectroscopy of van der Waals molecules in supersonic flow. Characteristics of electron states in $CdKr$ and Cd_2 " won an award of the Board of the Faculty of Physics, Astronomy and Applied Computer Science of the Jagiellonian University.

In 2001-2003, I was an investigator in research project KBN 5 P03B 037 20 "Properties of van der Waals bonding in diatomic molecules in different regions of internuclear distances". I was also involved in the implementation of several grants from the Central Research Reserve of the Jagiellonian University: of the Rector (2000, 2001) and of the Faculty Dean (in 2000 and 2002).

During the PhD studies, I was also involved in the implementation of international research projects related to the use of equipment available in the Laser Spectroscopy Group, for different purposes than the molecular spectroscopy. I was cooperating with prof. R. Djulgerova (Institute of Solid State Physics, Bulgarian Academy of Sciences) in studying the dynamics of optogalvanic signal induced in the Ne hollow-cathode discharge, and with Dr. Pierre-Jean Nacher (Laboratoire Kastler Brossel, ENS Paris) in testing the effectiveness of metastability exchange optical pumping of 3He gas.

Research work after obtaining a doctoral degree

The next stage of my research was a two year internship (2004 and 2005) at the University of Windsor in Canada, in the group of professor J.W McConkey. The work carried out by the Canadian research group was focused on the measurement of cross sections for collisions of atoms and compounds with electrons and photons. The results of such experiments are important in the fundamental research in physics and chemistry, but also have direct applications in industry, environmental protection, etc. Use of various types of targets in the process of scattering and the simultaneous use of a wide variety of measurement techniques, such as electron, mass and optical spectroscopy, time of flight measurements and laser spectroscopy, yielded high quality results.

My experiment concerned measuring values of cross sections for the interaction of electrons and cesium atoms in a magneto-optical trap. Cesium is perhaps the most interesting alkali target because of potential practical applications, such as in atomic clocks or ion propulsion schemes for space vehicles. Further, being the heaviest of the alkalis, caesium is also of great interest from a theoretical point of view because relativistic and atomic structure effects should be significant for this element.

The use of a magneto-optical trap for collision cross section measurements was a new concept (the first such experiment was performed in 1995 for rubidium atoms) offering a number of advantages over more conventional techniques based on measurements in atomic beams. The main advantage of this technique consisted in the fact that knowledge of the absolute target density was not required. The loss of atoms from the trap, due to electron collisions, was monitored by measuring changes of fluorescence from trapped atoms and related directly to the cross section and electron flux through the trap. Furthermore, it was possible to obtain absolute cross section data for excited species because the process of atom trapping resulted in the preparation of a target with a large fraction of such species. Finally, the use of various procedures and test sequences made it possible to study various processes that added up to the total, electron-induced, cross-section.

Expansion of the existing experimental system and development of new measurement methods, resulted in the determination of the absolute values of cross sections for the interaction of electrons and cesium atoms. The most important results comprised: determination of the total cross-section for electron impact on Cs for a wide range of electron energy, and the first experimental determination of the electron-impact ionization cross sections out of the ground and 6^2P excited states of caesium using a novel measuring technique. These results were published and presented at several conferences.

After returning to Poland, for a short time, I continued research work in the Molecular Spectroscopy Group at the Department of Atomic Optics, Jagiellonian University. I conducted experimental studies and calculations of electronic potential curves of van der Waals molecules ($CdRG$ ($RG =$ noble gas) and Cd_2) using IPA (Inverse Perturbation Method). One of the main results of this work was the determination, on the basis of rotation fluorescence spectra of $^10_u+(5^1P_1) \leftarrow X^10_g+$ transition, of the bond length of the Cd_2 molecule ground state, which in turn made possible a quantitative assessment of the size of covalent admixture to the binding of the dimer. After changing my employment, between 2007 and 2009, I still cooperated with the research group of professor Jaroslaw Koperski and this cooperation resulted in publishing a series of five articles on the nature of binding of the cadmium dimer and cadmium-noble gas molecules.

In 2006, I started cooperation with professor Roman Kozłowski leading research on the preservation of cultural heritage at the Jerzy Haber Institute of Catalysis and Surface

Chemistry Polish Academy of Sciences (ICSC) in Krakow. In the same year, I received a grant from the Ministry of Science and Higher Education for Young Scientists (POL-postdoc II), which made possible my employment at the ICSC. From that moment, I began research on climate-induced damage of historic objects. My research was focused on the analysis of risks associated with the response of paintings on wood – one of the most vulnerable category of historic objects – to variations of environmental conditions. The problem, whose solution has been until now the main goal of my research, is to develop non-invasive methods to monitor the micro-damage progress in art objects. Since both historical objects and their destruction processes are very divers, I decided to make use of multiple complementary methods of their characterization.

For the analysis of surface layer damage, I applied active thermography and speckle interferometry, which replaced laser scanning vibrometry previously used in professor Kozłowski's group. Speckle imaging methods proved to be extremely sensitive and effective in mapping cracks and delaminated parts of decorative layers on the surface of objects. Systematic efforts on adapting these methods to the operation in museum conditions resulted in constructing a portable system and the development of research methodology that allows precise measurements to be performed outside the laboratory – on exhibition, inside historic buildings. The most important outcome of the study was the development of a fully automated, quantitative method for characterizing the state of preservation of the object surface with a sub-micrometer accuracy. The results obtained using this method were the basis for elaborating climate control strategy in the Palace of the Bishop Erazm Ciołek (a branch of the National Museum in Krakow) and in a historic church in Hedalen, Norway. The developed method of direct tracing damage in historic objects was also used in the Victoria and Albert Museum in London and the National Museum in Warsaw. Successful application of the speckle interferometry for the analysis of the preservation state of historic objects was possible owing to a cooperation with NIKU (Norwegian Institute for Cultural Heritage) within the frame of a Polish-Norwegian research grant, and my involvement in the activities of the COST Action IE0601 (Wood Science in Conservation of Cultural Heritage) .

In parallel to the research on the application of the optical techniques, I decided to further develop the acoustic emission method, already used in professor Kozłowski's research group. This method consists in recording sound and ultrasound pulses generated during micro-cracking of materials. It is complementary to the speckle interferometry as it provides information about defects generated not only on the surface but also in the bulk of the material. Furthermore, acoustic emission allows the damage development to be traced in real-time and thus allows a correlation to be established between actual damage and environmental instabilities which caused them. Collaboration with research groups from the University of Stuttgart and Bologna within the frame of the European project "SMooHS" as well as consultations and exchange of experience within members of the COST Action FP0802 (Experimental and Computational Characterization Techniques in Wood Mechanics) helped me to define

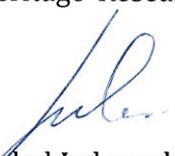
requirements for the measurement technique to be used in historic buildings. Calibration measurements (correlation between damage in various materials with energy and frequency of the measured signals) enabled quantitative methods for assessing the progress of micro-damage in art objects to be developed, whereas the use of the anti-correlation method made it possible to perform the measurements in presence of high environmental noise.

Monitoring of climate-induced changes in historic textiles and canvas has been the third important topic of my research. Neither the interferometric methods, nor the sound methods can be effectively used for analysis of the damage progress in textile objects. To monitor precisely deformation of these objects, fibre Bragg grating sensors were utilized. The development work was done in cooperation with scientists from the Institute of Physics, Jagiellonian University. The measuring system was tested on historic textiles displayed in the National Museum in Krakow and on mock canvas painting in transport conditions and during exhibition in a gallery. The developed monitoring technique has contributed to the understanding which factors are mainly responsible for damaging textile objects during their exhibition at the museum conditions and opened the perspective for a widespread use of the fibre sensors in continuous monitoring of various (not just textiles) objects.

In my studies, collaboration with national and international research institutes and university departments specializing in the field of non-destructive testing and analysis of physical properties of materials is as important as contacts with institutions involved in the preservation of cultural heritage collections. Almost from the very beginning of my work in the ICSC, I was involved in practical investigations of the National Museum in Krakow such as identification of hazards during transportation of a painting collection from the Gallery of the 19th-Century Polish Art at Sukiennice during the renovation of the building and determination of risks associated with exhibiting panel paintings reinforced by cradling constructions in non-conditioned galleries. I also coordinated a research project aimed at developing a strategy for sustainable climate control for preserving collection of moisture sensitive objects. Cooperation with the Academy of Fine Arts in Krakow, the Malbork Castle Museum, the National Museum in Warsaw, the Victoria and Albert Museum in London and other, has allowed me to apply the developed experimental techniques, and to implement the developed conservation guidelines.

During the employment in the ICSC, I have taken an active part in teaching and popularizing activities of the Institute. Since 2010, I have been the Deputy Director for Operations of the Institute and, since 2013, a head of the Cultural Heritage Research Group.

Kraków 17.02.2015



Michał Łukomski