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Synchrotron radiation microtomography of musical instruments: a non-destructive monitoring technique for insect infestations

Abstract - X-ray computed tomography is becoming a common technique for the structural analysis of samples of cultural relevance, providing luthiers, art historians, conservators and restorators with a unique tool for the characterization of musical instruments. Synchrotron-radiation phase-contrast microtomography is an ideal technique for the non-destructive 3D analysis of samples where small low-absorbing details such as larvae and eggs can be detected. We report results from the first feasibility studies performed at the Elettra synchrotron laboratory, where the 1494 organ by Lorenzo Gusnasco da Pavia has been studied. Together with important information about the structural conditions, the presence of xylophages could be detected and characterized.

Key words: cultural heritage, musical instruments, xylophages, x-ray imaging.

INTRODUCTION

Several types of insects infest wooden musical instruments, and damage inflicted by wood-destroying insects can occur over a long time before detection. While it is critical to assess the amount of actual and potential damage, it is even more important to recognize this kind of event at an early stage and, if possible, to identify the insects before taking appropriate control measures. In case of instruments of great historical, artistic and economic value, a monitoring technique must necessarily be non-invasive and compatible with their typical dimensions. Clinical computed tomography has been applied successfully to evaluate both the normal structure and abnormal conditions that may affect an instrument (Sirr & Waddle, 1997; 1999; Gattoni *et al*., 1999; Iwamoto *et al*., 2002). The main limitation in the application of the technique, however, is related to the limited spatial resolution of commercial instruments, where the typical voxel size is of the order of 0.4x0.6x0.6 mm^3. Every defect with lateral dimensions smaller than this value cannot, therefore, be detected with state-of-the-art hospital instruments. The dynamical range of the detectors usually employed, moreover, are not compatible when metal parts such as strings in bowed instruments or keys in woodwind instruments are present and cannot be removed. Additionally, conventional absorption radiology is not the ideal technique when soft matter details need to be detected inside harder matrices.

As a last consideration, it is not possible to adequately control environmental parameters such as temperature and humidity when delicate instruments need to be analysed. In this article we describe the phase-contrast X-ray microtomography (Mancini *et al*., 2006; Rigon *et al*., 2010) as a non-invasive tool for the analysis of insect infestation in wooden musical instruments. Conservators and restorators can obtain digital three-dimensional morphological information about the samples without the need of removing metal parts from their instruments and, thanks to the dimensions of the typical experimental setups, a precise monitoring and control of the environment can be achieved during the data acquisition.

MATERIALS AND METHODS

The positive organ of Lorenzo da Pavia (1494)

The only surviving paper-pipe organ belongs to the collection of musical instruments of the Musei Civici Veneziani, and kept at the Museo Correr (Fig. 1). The author of the instrument is Lorenzo Gusnasco da Pavia, well known for his relationship with the most important families of his age (Prizer, 1982). While the original destination of the organ, built in 1494, is still not clear (the previous identification with the instrument

Fig. 1 - The 1494 positive organ of Lorenzo Gusnasco da Pavia.

built for Mattia Corvino, King of Hungary (Sansovino, 1581; Haraszty, 1940) is at least uncertain) we know that it has been bought by the Museo Correr around 1874 (Barozzi, 1880). The documentation on the analysis and restoration of the organ is negligible, and the first complete study has been published in 1976 by Marco Tiella (Tiella, 1976). The importance of the instrument, however, has always limited the kind of analysis performed, and the non-destructivity of the techniques has always been a fundamental requirement.

Phase-contrast radiology

In conventional radiology the image formation relies on the X-ray absorption properties of the sample and can be expressed by means of geometrical optics. The image contrast is originated by a variation of density, composition or thickness of the sample and is based exclusively on the detection of amplitude variation of the transmitted X-rays. Information about the phase of X-rays is not taken into account. The main limitation of this technique is the poor inherent contrast in samples with low-Z composition: indeed this is the case of “soft matter” which is considered, in the common sense, as transparent to X-rays. Contrary to absorption radiography, “phase-contrast imaging techniques” are based on the observation of the phase shifts produced by the object on the incoming wave. They are described by means of wave optics. Absorption and phase shifts are effects occurring to X-rays crossing any kind of materials. Their relationships is considered in the definition of the material complex index of refraction n, that in the X-ray region, slightly differs from unity: $n = 1 - \delta + i\beta$, where δ is related to the refractive properties and β determines the absorption. In the energy range between 15 and 25 keV, the phase shift term δ (of the order of 10^{-7}) can be up to 1000 times greater than the absorption term β (of the order of 10^{-10}), therefore it is possible to reveal phase effects even if the absorption is negligible (phase objects). The observation of the local variations in the optical path-length, determined by variations of δ, is related to Fresnel diffraction. In general, phase information can be accessed if the X-ray source has a high spatial coherence as in the case of synchrotron light sources (Snigirev *et al.*, 1995; Baruchel *et al.*, 2000) like ESRF in France or Elettra in Italy. Several approaches for phase-contrast radiology have been reported (Fitzgerald, 2000). Among these, the phase-contrast (PC) radiography technique based on free space propagation can also be called in-line holography in analogy with optics and has a quite simple application: the PC set-up is the same of conventional radiography with the difference that the detector is positioned at a certain distance d from the sample. The X-rays exiting from the sample propagate in the free space until they reach the detector. Free space propagation transforms phase modulation of the transmitted beam into amplitude modulation. Contrast is originated from interference among parts of the wavefronts that have experienced different phase shifts. According to the choice of d with respect to the size of the feature to be identified perpendicularly to the beam direction, one may discriminate between two regimes: the edge detection regime ($d \ll a^2/\lambda$, where λ is the X-ray wavelength) and the holography regime ($d \approx a^2/\lambda$). In the edge detection regime images can be used directly to extract morphological information. The produced diffraction pattern

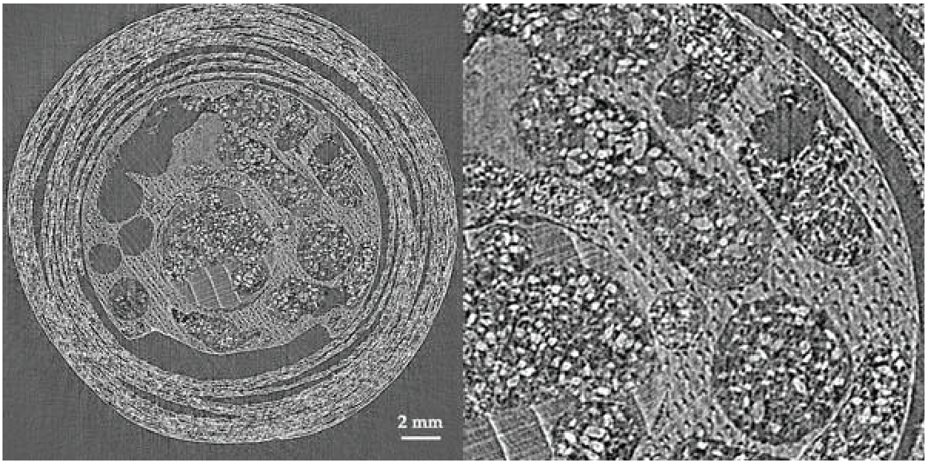

Fig. 2 - Left: virtual slice of a paper pipe at the wooden foot position taken at the SYRMEP beamline. Right: inset showing the different wood qualities and the presence of larvae.

appears superimposed to the conventional absorption pattern (if any) on the detector and contributes mainly to enhance the visibility of the edges of the sample features.

The microtomographic analysis

In order to obtain more detailed information about the internal structure of the paper pipes, we used the SYRMEP beamline (Abrami *et al*., 2005) and the TOMOLAB facility of Elettra, the italian synchrotron laboratory of Trieste. The synchrotron images have been recorded by a water-cooled 12/16 bit, 4008 x 2672 full frame CCD camera with 4.5 micron pixel size and a field of view of 18 x 12 mm^2, coupled to a Gadox scintillator placed on a straight fiber optics coupler. During data acquisition, samples were rotated 180° around an axis perpendicular to the incident beam with a sample-to-detector distance of 20 cm and a beam energy of 20 keV. Projection images were recorded at 0.125 degree rotation step for a total of 1440 projections for each sample. These parameters were optimized in a preliminary step by imaging several samples under different beam energy, phase contrast and resolution conditions.

A typical reconstructed slice of a pipe at the level of the wooden foot is shown in Fig. 2, where the experimental parameters have been optimized for the definition of the number and thickness of the paper layers, as well as the overall condition of the paper and wood foot structure. The final spatial resolution is about 10 microns. We can evaluate the present situation of the paper pipe (which appears to be more critical in comparison with other points of the same pipe), but we can also extract important information about the wooden part. The different kinds of wood used by Lorenzo Gusnasco

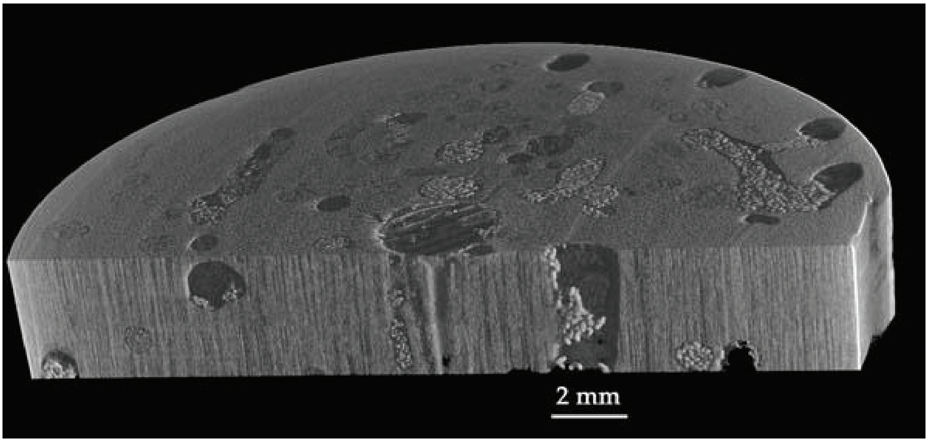

Fig. 3 - 3D rendering of a slice of a wooden foot taken at the TOMOLAB facility.

can be determined with great precision, and we also have a clear view of the presence of wormholes caused by the infestation of powderpost beetles. Thanks to the phase-contrast approach we can also detect the presence of larvae inside the wooden foot.

In order to compare the synchrotron results with a state-of-the-art conventional system, we repeated the same analysis at the TOMOLAB facility (Polacci *et al.*, 2009). TOMOLAB is a micro-CT system equipped with a sealed microfocus X-ray tube, which guarantees a focal spot size of 5 μm, in an energy range from 40 up to 130 kV, and a maximum current of 300 μA. A water cooled CCD camera providing a good combination between a large field of view (49.9 mm × 33.2 mm) and a small pixel size (12.5 × 12.5 μm^2) is used as detector. Thanks to the cone-beam geometry, it is possible to achieve a spatial resolution close to the focal spot size (Feldkamp *et al.*, 1984; Kak & Slaney, 1987), even if in this case spatial resolution has been partly sacrifice to achieve a wider field of view. Thanks to the small size of the X-ray tube focal spot, a limited but clearly detectable phase contrast effect can be achieved (Wilkins *et al.*, 1996), especially when relatively low energies are involved and object-to-detector distances are in excess of 30 cm. Thanks to its geometry, even this setup allows to perform phase-contrast measurements. The tomographic scan of the sample was performed with a pixel size of 20 μm^2, with a tube voltage of 45 kV and a tube current of 177 μA. A total number of 1800 projections were collected (source-to-sample distance = 45 cm and source-to-detector distance = 55 cm). In Fig. 3 the paper pipe has been digitally removed and only the wooden part is shown, and we choice a different graphical representation in order to show the different ways that the data can be displayed. Again, the womholes are well defined as well as the presence of the powderpost beetles larvae.

CONCLUSIONS

Phase-contrast microtomography looks like a promising non-invasive technique for the monitoring and characterization of insect infestation in wooden musical instruments, but can be applied, even in a bidimensional configuration, to other samples of artistic and historical interest. During the morphological analysis of ancient violins of the Cremonese school, the synchrotron radiation approach has not induced any degradation of the instrument. Additional mesaurements could show if the typical exposure times of 30-60 minutes could have the additional effect of killing any powderpost beetles still present inside the samples.

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REFERENCES

Abrami A., Arfelli F., Barroso R.C., Bergamaschi A., Bille F., Bregante P., Brizzi F., Casarina K., Castelli E., Chenda V., Dalla Palma L., Dreossib D., Fava C., Longo R., Mancini L., Menk R.-H., Montanari F., Olivo1, A., Pani S., Pillona A., Quai E., Ren Kaiser S., Rigon L., Rokvic T., Tonutti M., Tromba G., Vascotto A., Venanzi C., Zanconati F., Zanetti A., Zanini F., 2005 - Medical Applications of Synchrotron Radiation at the SYRMEP beamline at ELETTRA. Nuclear Instruments and Methods in Physics Research, section A, 548: 221-227.

Barozzi N., 1880 - Doni fatti al Museo Correr fino al 1880 e cenni intorno al suo collocamento nel nuovo edificio. Naratovich, Venice.

Baruchel J., Cloetens P., Härtwig J., Ludwig W., Mancini L., Pernot P., Schlenker M., 2000 - Phase imaging using highly coherent X-rays: radiography, tomography, diffraction topography. Journal of Synchrotron Radiation, 7: 196-201.

Feldkamp L.A., Davis L.C., Kress J.W., 1984 - Practical cone-beam algorithm. Journal of the Optical Society of America, section A1: 612-619.

Fitzgerald R., 2000 - Phase sensitive X-ray imaging. Physics Today, 53: 23-36.

Gattoni F., Melgara C., Sicola C., Uslenghi C.M., 1999 - Unusual application of computerized tomography: the study of musical instruments. Radiol Med, 97: 170-173.

Haraszty E., 1940 - A propos de l'orgue de Mathias Corvin du Musée Correr à Venise. L'Orgue, 21: 7-17.

Iwamoto J., Kenmochi Y., Kotani K., Nagasawa I., 2002 - Extraction of a 3D graph structure of wormholes in a wooden statue of Buddha by X-ray CT image analysis. Proceedings of the Fifth Asian Conference on Computer Vision, ACCV2002: 864-870.

Kak A.C., Slaney M., 1987 - Priciples of Computerized Tomographic Imaging. IEEE Press, New York.

Mancini L., Tromba G., Zanini F., 2006 - Structural microanalysis with synchrotron radiation: archaeometric applications at Elettra. Journal of Neutron Research, 14: 75-79.

Polacci, M., Baker D. R., Mancini L., Favretto S., Hill R. J., 2009 - Vesiculation in magmas from Stromboli and implications for normal Strombolian activity and paroxysmal explo-

sions in basaltic systems. Journal of Geophysical Research, 114: B01206-B01220.
Prizer W.F., 1982 - Isabella d'Este and Lorenzo da Pavia, 'Master Instrument-Maker'. Early Music History, 2: 87-127.
Rigon L., Vallazza E., Arfelli F., Longo R., Dreossi D., Bergamaschi A., Schmitt B., Chen R., Cova M.A., Perabò R., Fioravanti M., Mancini L., Menk R.H., Sodini N., Tromba G., Zanini F., 2010 - Synchrotron-radiation microtomography for the non-destructive structural evaluation of bowed stringed instruments. e-Preservation Science, 7: 71-77.
Sansovino M.F., 1581 - Venetia città nobilissima et singolare. Curti, Venice: 379-380.
Sirr S.R., Waddle J.R., 1997 - CT analysis of bowed stringed instruments. Radiology, 203: 801-805.
Sirr S.R., Waddle J.R., 1999 - Use of CT in detection of internal damage and repair and determination of authenticity in high-quality bowed stringed instruments. Radiographics, 19: 639-646.
Snigirev A., Snigireva I., Kohn V., Kuznetsov S., Schelokov I., 1995 - On the possibilities of x-ray phase contrast microimaging by coherent high-energy synchrotron radiation. Review of Scientific Instruments, 66: 5486-5492.
Tiella M., 1976 - The positive organ of Lorenzo da Pavia. The Organ Yearbook, 4: 4-15.
Wilkins S.V., Gureyev T.E., Gao D., Pogany A., Stevenson A.W., 1996 - Phase-contrast imaging using polychromatic hard X-rays. Nature, 384: 335-338.

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