

SYNCHROTRON-RADIATION MICROTOMOGRAPHY FOR THE NON-DESTRUCTIVE STRUCTURAL EVALUATION OF BOWED STRINGED INSTRUMENTS

TECHNICAL PAPER

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Feasibility studies have been carried out at the SYRMEP beamline of the Elettra synchrotron laboratory in Trieste with the aim of demonstrating the advantages and evaluating the effectiveness of synchrotron radiation X-ray microtomography as a suitable technique for non-destructive analysis of bowed stringed instruments. The particular geometry of the X-ray beam and the use of a novel detector allow structural evaluation of the main details of the instruments with unprecedented richness of details. This, in turn, will allow precise dendrochronological investigation of historical violins, as well as the characterization of their structure, defects, wood thickness and density.

1 Computed Tomography Structural Analysis of Bowed Stringed Instruments

Computed tomography (CT) provides the modern luthier and acoustic scientist with a unique tool for characterization of normal structure, defects, and repair and for accurate measurements of wood thickness and density.^{1,2} CT-derived information aids in the replication of original masterpieces and have an important role in the valuation, insurance, and identification of valuable stringed instruments such as violins, violas and cellos.

The economic value of an historical instrument may decrease considerably if a defect or repair is discovered. For example, a violin with a crack in the sound post region of the back plate is conventionally valued at only 50% of the same instrument without the defect. Moreover, it is well known that many serious abnormal conditions may be concealed with glue, filler material, retouch, or varnish. Abnormal conditions that affect bowed stringed instruments include cracking, warping, and wormholes (caused by the infestation of larvae).

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Steven Sirr and John Waddle are the authors of the first fundamental works where clinical CT has been applied to the study of ancient and modern violins, demonstrating the potentiality of the technique.^{1,3} Varying degrees of damage (such as wormholes, air gaps, plastic deformation of wood) or repair (glue lines, filler material, wooden cleats and patches) invisible at visual inspection were detected in 17 historical violins and cellos crafted between 1633 and 1872 by Cremona masters such as Guarneri del Gesù, Amati and Stradivari. Additionally, CT analysis allowed identification of the internal wood grain pattern unique to each instrument, facilitating verification of authenticity and protection against loss, theft or forgery for violins which can be valued in excess of 1 M€.³

Clinical CT (the computed tomographic system used in hospitals), whose results have been evaluated with special developed image processing software, has also been used to measure the density differences of wood between different points of classical and modern violins.⁴ These differences in density differentials may reflect similar changes in stiffness distributions, which could directly impact vibrational efficacy or indirectly modify sound radiation via altered elastic characteristics. Either of these mechanisms may help explain the acoustical differences between the classical and modern violins.

The main limitation in the application of clinical computed tomography to the structural analysis of bowed instruments, however, is related to the limited spatial resolution of commercial instruments, where the typical voxel size (the voxel is the 3D version of the common 2D pixel) is of the order of 0.4x0.6x0.6 mm³. Every defect with lateral dimensions smaller than this value cannot, therefore, be detected with state-of-the-art hospital instruments.

2 Dendrochronology of Historical Violins

Dendrochronological analysis is a well established wood dating technique that has been demonstrated to be a powerful system in various areas of research.^{5,6} Dendrochronological dating is based on the fact that annual growth rings are influenced by the environmental conditions in which a tree grows. Variables such as rainfall, temperature and humidity result in a pattern in the sequence of ring widths, which is usually similar and distinctive in trees of the same species growing in the same conditions, i.e. the same area. This allows the researchers to construct a reference chronology, which is a sequence of ring widths calculated by averaging the values from trees of a known age

from the same region. If these values on wood of unknown age fit this scheme, the wood can be dated.⁷

In the field of musical instrument research, dendrochronology has found application in the dating of bowed stringed instruments.^{8,9} The construction of most members of the violin family involves the use of maple (*Acer platanoides* L.) or sycamore (*Acer pseudoplatanus* L.) for the back, sides and neck. The front plate is generally assembled with Norway spruce (*Picea abies* L. Karsten), due to the ideal acoustic properties related to the stiffness/weight ratio of the wood from this particular species. The manufacturing process usually results in a two-pieces front with a longitudinal joint in the centre of the violin, with the youngest growth rings which join together at the centre of the plate. Usually only the spruce front plate is used for dendrochronological investigation as neither maple nor sycamore can be used, due mainly to their unreplicable growth characteristics.

All measurements are usually made on the widest part of the lower section of the front plate in order to maximize the number of growth rings available. This enables measurement of the grain in the radial plane rather than the conventional measurement in cross-section. In a front view, the left and right sides of the spruce front are referred to as the bass and treble sides, respectively. Typical measurements are made with a stereo microscope mounted on a horizontal, hand-adjusted traveling carriage under which the instrument can be fixed. The absolute position of the microscope is recorded with the use of a linear encoder mounted on the traveling carriage. The encoder is connected to a display unit that provided character output to a PC. This experimental setup usually allows measurement to an accuracy of 10 µm.

3 X-ray Microtomography with Synchrotron Radiation

X-ray microtomography (µCT) is an imaging technique with major potential applications in the cultural heritage domain, and the new possibilities offered by the last generation synchrotron sources have increased the interest in this technique.¹⁰⁻¹² The main characteristics of synchrotron radiation are the continuous spectrum, extending from infrared to hard X-rays, the high intensity and the high spatial coherence of the X-ray beam. These features allow to obtain fast exposure times, to tune the photon energy as a function of the sample characteristics and to use digital subtraction techniques.¹³ Monochromaticity and high collimation of the beam, moreover, allow a data analysis with

reduced artefacts and a better quality. Furthermore, phase-sensitive imaging techniques using highly coherent, hard X-rays from third-generation synchrotron sources have the additional advantage to allow imaging of samples with very low absorption contrast, such as light-element glues and consolidants.¹⁴ It has been demonstrated that the fine interference structure of phase-images is very sensitive to density variations and internal structure of the sample. Phase-sensitive μ CT exhibits enhanced phase contrast in regions of a highly localized change in the refractive index of the sample, such as its borders or interfaces between the original object and included materials. The tomogram is then an outlined image of those domains, while in conventional imaging the main contrast formation is due to absorption and edge detection is strongly limited.¹⁵ All these measurements can be performed in a completely non invasive way in monitored environments, where temperature and humidity can be carefully controlled.

One of the main limitations of synchrotron radiation μ CT is related to the limited field of view (FOV) of the detector used for experiments (compared with detectors for conventional tomography), because of the particular geometry of the X-ray beam and the lateral dimensions of commercially available high-resolution detectors. In this article we describe two approaches designed to overcome this limitation: the use of large detectors coupled with laminar X-ray beams and the use of local area microtomography.

4 Microtomography with Large Detectors

The detector utilized for the acquisition of a complete slice of the violin is a prototype called “Phase Imaging for Clinical Application with Silicon detector and Synchrotron radiation” (PICASSO) and developed by the Italian Istituto Nazionale di Fisica Nucleare (INFN).¹⁶ The PICASSO detector has been devised in order to perform medical imaging (chiefly mammography) taking advantage of the particular features of synchrotron radiation beams.¹⁷ This detector resulted very attractive for the applications herein presented thanks to the capability of covering the full width of the beam (210 mm) with a high spatial resolution (0.05 mm).

PICASSO is a silicon microstrip detector, similar to those widely used in high-energy physics experiments. However, unlike the latter, it is utilized in the “edge-on” configuration, i.e. with the photons impinging on the thin side of the sensor, parallel to the strips. This configuration matches the laminar geometry of the beam and provides a linear array

of pixels, where the aperture of each pixel is determined by the strip pitch (0.05 mm, horizontal) and the sensor thickness (0.3 mm, vertical). The spatial resolution is consistent with this geometric aperture and can be further improved in the vertical direction by using a slit system to reduce the height of the beam in front of the sample.

Moreover, the detector is operated in single-photon counting and it is read out by a high-rate electronics based on the Mythen-II application-specific integrated circuit (ASIC), developed by the Paul Scherrer Institut (PSI) detector group for powder diffraction experiments at the Swiss Light Source. Each pixel is wire-bonded to one channel of the Mythen-II ASICs and its signal is processed individually throughout the read-out electronics. The single-photon counting approach allows to maximize the contrast resolution (preserving the quantum nature of the information carried by the photon beam) and to overcome the limitations in the dynamic range, which are typical of charge-integration detectors such as charge-coupled devices (CCDs) and flat panels.

The PICASSO prototype utilized is actually a double-layer detector, where each layer is framed by an aluminium structure, which holds both the silicon sensor and the read-out electronics. On each layer, two sensors, respectively 90 and 120 mm wide, are glued side-by-side in order to achieve the aforementioned 210-mm width, which corresponds to 4200 pixels. However, the tomographic acquisition herein presented has been acquired utilizing

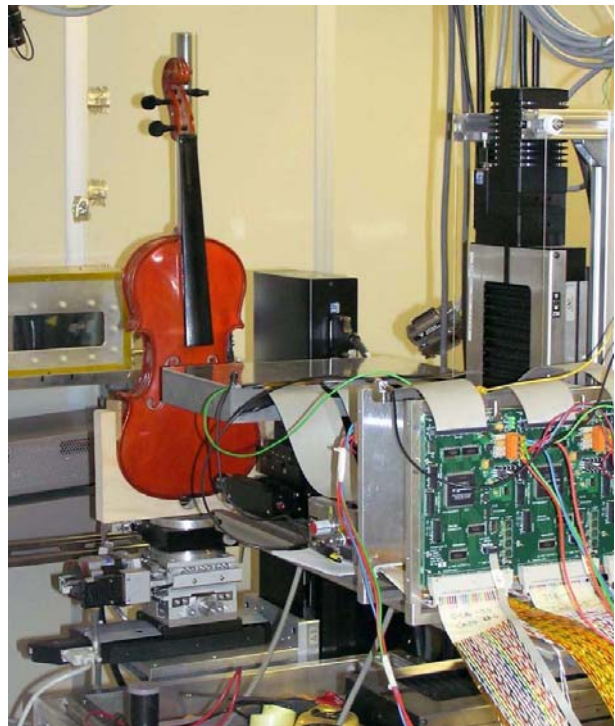


Figure 1: The violin during data acquisition at Elettra with the PICASSO detector.

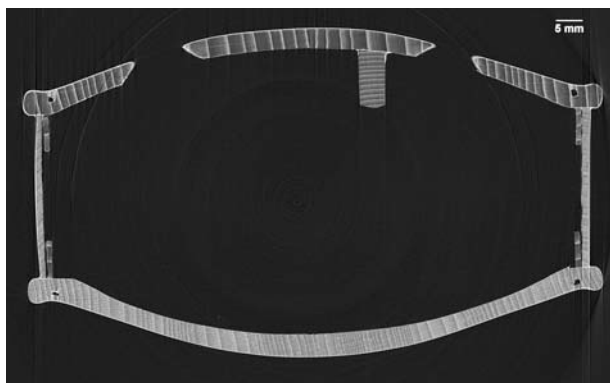


Figure 2: Transaxial μ CT scan of a student violin taken at SYRMEP. The section has been taken at the middle bout, at the level of the f-holes. Note the bass bar and the linings which attach the front and back plates to the ribs.

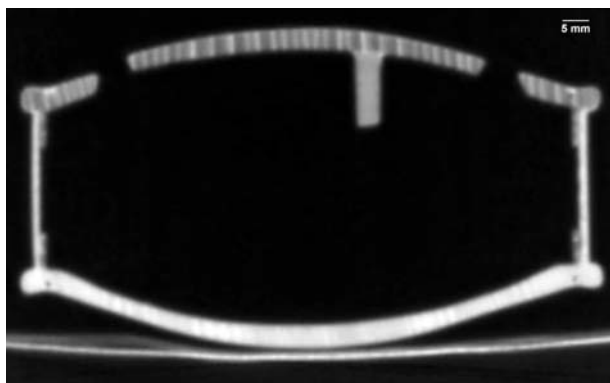


Figure 3: Transaxial CT scan of the same violin of fig. 1 taken with a state-of-the-art clinical instrument (Toshiba Aquilion of the Azienda Ospedaliera - Università di Trieste, helical scan 120 kVp, 512x512 matrix, 0.5 mm slice thickness, 0.5 s exposure time, 0.485/0.485 pixel spacing; Torace protocol).

only the 120-mm-wide sensor of the bottom layer, which was wide enough to collect the projected image at all angles. The experiment was carried out at the SYRMEP beamline¹⁸ of the Elettra Laboratory in Trieste, Italy. The beam, about 0.05 mm in height, was centred on the 0.3-mm-high sensor, and the energy was set to 23 keV. 3600 projections have been acquired over 180 degrees, with an angular increment of 0.05 degrees and an acquisition time of 1 s per projection. The data have been analysed following a procedure similar to the one described in Chapter 5.

In order to show the potentiality of this approach, we have analysed an inexpensive student violin through the middle bout, at the level of the f-holes (Figure 1).

The transaxial μ CT scan of this violin (Figure 2) should be compared with a scan taken from the same violin and in the same position, but with a state-of-the-art clinical instrument (Figure 3). The increase of the spatial resolution by one order of magnitude allows the observation of several details which cannot be detected with medical instruments.

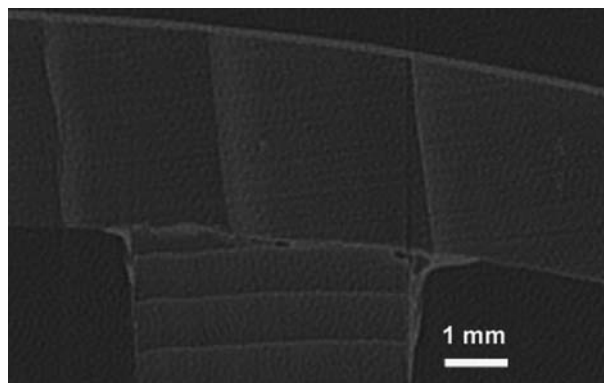


Figure 4: Detail of Figure 2 showing the bass bar and the glue used to attach it to the front plate.

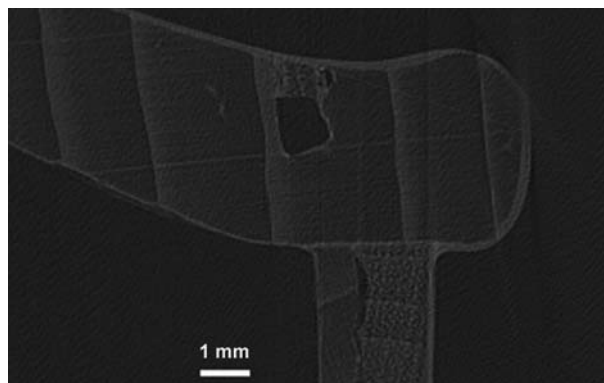


Figure 5: Detail of Figure 2 showing the front plate, one rib and the relative lining.

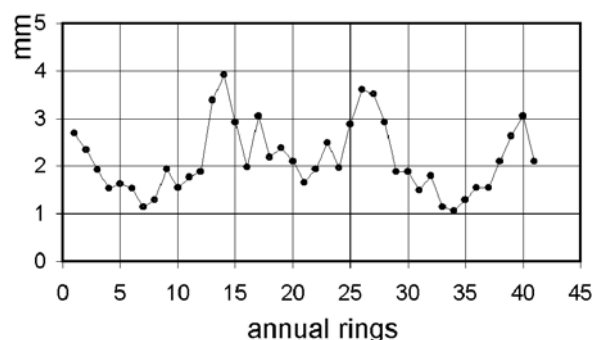


Figure 6: Tree rings measurement taken from the front plate μ CT scan. The ring widths are indicated by the dark points on the curve.

As an example, an expanded image of the bass bar, parallel to the long axis of the violin and attached to the inner surface of the front plate, shows details of the adhesion with the plate which cannot be seen with other means (Figure 4).

The same considerations apply to the detail showing the lining attaching the front plate to one the ribs of the violin (Figure 5). From these images it is also clear that the growth rings of the front plate can be measured with precision, allowing a

careful dendrochronological analysis of the wood used by the luther.

A tree ring measurement has been retrieved from the microtomography data of the front plate, similarly to ref. 7, where the ring widths are indicated by the points on the curve (Figure 6). Ring-width patterns like this are usually compared with reference chronologies in order to cross-date stringed bowed instruments from the same area.

The spatial resolution of the experimental setup also allows the determination of the tree wood used for the different parts of the violin.

5 Local Area Microtomography

From the mathematical point of view, computed tomography is related to the analysis of the three-dimensional distribution of the real or imaginary part of the refractive index inside an object from transmission images collected at different incident angles. The filtered backprojection algorithm (a computer implementation of the so called approximate inversion formula¹⁹) is the most popular reconstruction method. In many practical situations it is important to minimize the FOV of the imaging system in order to increase the spatial resolution of the reconstructed image, but when the object of interest is larger than the FOV, the measured projections are truncated and one is faced with a local tomography reconstruction problem. This is a long-standing problem associated with the mathematical properties of the Radon transform, namely the non-locality of the CT reconstruction.²⁰ This implies in practical terms (in the case of the parallel-beam condition typical of synchrotron sources) that one always has to irradiate and acquire the whole axial slice of a sample, even when the actual interest is limited to a small region inside that slice. As a consequence, it is generally impossible to reconstruct, with the usual experimental and mathematical methods, the distribution of the refractive index inside a sample that is larger than the FOV of the CT system. Undesirable implications of this property are easy to appreciate, particularly in the case of samples that are sensitive to the radiation dose (as is the case in medical CT), or require high-resolution imaging of small regions in a bulky sample.²¹ Methods for overcoming the non-locality of the CT reconstruction have been extensively investigated since the 1970s, and some promising new results have been also reported recently.²²

An alternative method is based on a different acquisition protocol based on a continuous scan. While conventional tomographic acquisitions are based on the sequential application of image inte-

gration and motor movement, during a continuous scan the sample rotates at a constant speed while projections are taken during the movement. Each projection is not related to a single angular position, but corresponds to a predetermined angular integration. When applied with suitable parameters, this approach can lead to a blurring of the structures on the planar images that are positioned at higher distance from the center of rotation of the sample, while structural details inside the FOV are not modified significantly. Choice of the angular step is critical, since details at the border of the FOV should not move by more than one pixel during a single planar acquisition. Rotation speed and acquisition time are chosen accordingly, taking into account also the characteristics of the X-ray detector. This experimental approach, rather than taking into account the mathematical features of local tomography, reduces the high frequency component of the signal related to structural details which are not in the FOV of the detector, and simplifies the reconstruction procedure needed to obtain a 3D description of the volume of interest.

The local area tomographic investigations were again carried out at the SYRMEP beamline. The violin, mounted on a rotation stage, was illuminated with monochromatic radiation (photon energy $E = 25$ keV) with a sample-to-detector distance $d = 140$ mm. A total number of 1800 projections of the sample were acquired for an exposition time of 5 s over a total rotation of 180 degrees. These parameters were previously optimized for phase contrast and resolution by imaging several samples under different conditions.

In this case we used a CCD camera (Photonic Science Ltd, Robertsbridge, UK), coupled to a Gadolinium Oxysulphide scintillator, with a 4008 (horizontal) x 2672 (vertical) pixels CCD with a pixel lateral size of $4.5 \mu\text{m}$ (field of view: 18 mm (h) x 12 mm (v)). The scintillator has been deposited directly onto the front surface of a 1:2 tapered magnifying fibre-optic.

The tomographic projections have been elaborated using *Syrmep_tomo_project*, a software written by F. Montanari.²³ In this software a set of routines allows the reconstruction of single slices or volumes; data can then be saved in several formats and subsequently loaded by other applications for visualization and analysis. The computer code is written in the IDL[®] language (ITT Visual Information Solutions, White Plains, NY, USA). The 3D reconstruction is performed using a filtered backprojection algorithm: for each projection an intensity map is recorded in the xy detector plane, then each intensity map is back projected along the normal to the projection itself. Projections are sub-



Figure 7: Slice from a Local Area Microtomography, showing a portion of the front plate between the f-holes. High resolution detail taken from the analysis of a whole violin can be appreciated, from the cellular structure and some defects of the wood to the quality of the varnish layer.

mitted to filtering procedures to eliminate noise and artefacts and, finally, the intensities are added for all the projections. Then, the reconstructed slices can be visualized as stacks of 2D images, or 3D views of the sample can be obtained by volume rendering procedures.

This approach gives results of unprecedented quality: details of the wood at the cellular level, as well as the detailed structure of the varnish layer can be appreciated (Figure 7). But the most important aspect of the analysis is related to the fact that the analysis has been performed non-destructively on the whole violin.

6 Conclusions

The combined approach of synchrotron radiation tomography, by the use of large detectors coupled with laminar X-ray beams and the use of local area microtomography, is an important tool in the non-

invasive three dimensional analysis of ancient and modern bowed string instruments. Besides obvious applications such as dendrochronological evaluations or quality analysis of musical instruments of great value, this approach can be of great help in the characterization of the outer layers, where both varnish and fillers are known to be in some way responsible of the overall performance.²⁴ More in general, this approach will be of fundamental importance in the evaluation and the definition of the restoration and conservation protocols for instruments of great historical, artistic and economic importance.

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