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A NEW SYSTEM FOR FAST ULTRASOUND-TOMOGRAPHY AT MARBLE SCULPTURES

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Abstract

The authors present a new ultrasonic system for the automatic determination of tomography on stone. The tomography can be determined with up to 32 ultrasonic transducers in a variable length holding system. The positions of the sensors are determined with a magnetic field tracking or optically with Aruco markers. The signal control is done by a single channel electronic with 32x multiplexer. In this way the determination of a tomography from 32 measuring positions could be reduced to approx. 1 hour.

Introduction

For about 50 years, various ultrasound-based methods have been developed for the examination of stone in the field of cultural heritage and building technology [1]. The review article by Chiesura et al. [2] and the book Architecture in Stone by S. Siegesmund and R. Snethlage [3] provide an informative overview. The speed of sound is the most widely used parameter in the investigation of marble, particularly the speed of sound of longitudinal waves used in 70 % of the articles sighted. The speed of ultrasound depends on the mineralogical, physical and mechanical properties [4], the degree of saturation of water [4, 5] and the degree of aging. The speed of sound in marble varies between 6000 m/s for freshly quarried material and 1500 m/s for heavily weathered material. Therefore, the determination of the speed of sound provides valuable information about the properties and condition of the marble. The most widespread method is the measurement of the sound velocity of longitudinal waves in transmission. Two ultrasonic transducers are mounted opposite each other on the stone to be examined and the sound velocity between them is determined. The transmission method can be modified in various ways by varying the arrangement of the transmitter and receiver in order to adapt them to different measurement tasks. There are, for example, the so-called radial transmission [6], the semi direct transmission [7] or refraction methods with surface waves [7]. A very meaningful technique is ultrasound tomography. It allows the representation of velocity distributions in cross-sections of marble objects and thus the assessment of the course of weathering [8] and the success of conservation measures [9]. Up to now, the measured values for the calculation of a tomography have been recorded manually with (digital) calipers and single-channel electronics with two ultrasonic transducers between 46 kHz and 250 kHz. First, the transmitter transducer is in any measuring position and the receiver transducer successively takes up the other measuring positions in the same plane. For each measuring position, the velocity of sound between the transmitter and receiver is determined. The amount of sound velocities that can be assigned to a transmitter position is called projection. After the data of the first projection has been acquired, the transmitter is moved to the next measuring position and the data set of the second projection is measured. A tomography of 32 measuring positions consists of 32 projections, i.e. 31 × 32 = 992 individual measurements. It is easy to understand that recording the data of an ultrasound tomography is very time-consuming and can take more than one working day. The ultrasound system presented here for the first time reduces the required time for a tomography with 32 measuring points to approximately 1 hour.

Methods

The new ultrasonic system consists of the following components: up to 32 ultrasonic transducers with a variable-length holding system, single-channel electronics with 32x multiplexer, a magnetic field tracking system and software for system control and tomography calculation. Figure 1 shows the ultrasound system mounted on a marble colomn of the Marmorpalais in Potsdam. The support system with the ultrasonic transducers (green) is mounted on the marble column, the electronics on the table in the background and the magnetic field generator on the wooden stand.

The ultrasonic sensors allow the system to determine times of flight in moderately weathered marble up to approx. 1 m thickness. The opening angle is approx. 60° and the aperture is 9 mm. In this way, the sound, which is coupled in at one point of the test object, can be received again on as many alternative positions on the object as possible. This ideally supports the planned tomographic measurement procedure. The transducer itself is as small and lightweight as possible, so that a high density of sensors can be achieved on the object to be measured without applying too much stress on the holding system or the object itself. Therefore and in order not to influence the magnetic field tracking, the housing of the sensors is made of polymer. In addition, the housing has a specially shaped end plate for safe contacting of a magnetic field sensor by a clamp. It is also important that the sensor can be coupled dry to the marble so that the object itself is not contaminated by a coupling medium. The transducer consists of a 200 kHz ceramic disc on a soft carrier. To optimize the energy transfer, an acoustic matching layer and a coupling layer made of soft polymer, which cannot be rubbed off by the marble, are applied.

The variable-length holding system consists of sensor plates that hold the sensors and flexible polymer connectors (figure 2). The sensor plates have the possibility to mount additional support screws. This prevents vertical tilting of sensor and belt at

Figure 1: the new system on a column of the Marmorpalais in Potsdam.

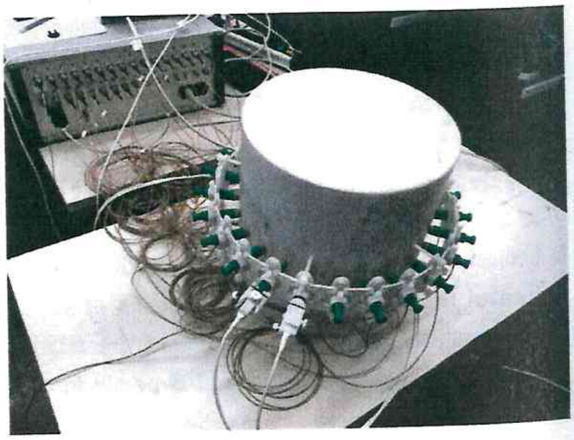

Figure 2: holding system with sensors on a marble cylinder.

the measuring object. The belt system can be assembled individually for each measuring object. By using flexible connecting elements of different lengths, a more or less high sensor density can be selected if required, or the overall length can be adjusted to suit the object.

The electronics consists of a single-channel transmitter and receiver unit that can generate transmission voltages of up to 1,000 Vpp and a multiplexer capable of switching 32 sensors to transmit or receive. The transmission voltage of up to 1,000 Vpp is provided by a transformer. Together wit the adjustable input gain of the electronic, the adjustable output power allows to adjust the received signal. The transformer has two primary windings and one secondary winding. The Amidon BN43-5170 suitable for the frequency range was selected as the core material. The two primary windings are connected in series. An adjustable DC voltage (0 to 48 V) is applied to the connection node. The other two ends of the primary winding are connected to a push-pull transistor circuit. Both transistors can independently connect the windings to ground. The transistors are controlled by a logic, that allows the frequency and signal coding to be adjusted. The maximum secondary output voltage can be varied by this principle adjustable over the primary DC voltage. The multiplexer has 32 channels to drive 32 ultrasound transducer. The multiplexer circuit consists of 32 switching elements, which can be switched on and off in transmit or receive regime independently. Since this application involves transmission voltages of up to 1000 Vpp, the multiplexer components of the HV series MicroChip used in standard systems could not be used. Therefore, discrete switching elements in the form of a "Solid State Power Relay" (CPC1988 of the manufacturer IXYS) were used. This is a MOSFET technology with an integrated opto-coupler. The 32 relay modules arranged in two banks are controlled by a multiplexer from Maxim. Their outputs are directly connected to the optically coupled input of the CPC1988. All outputs of the multiplexer can be activated by a microcontroller via its serial interface. If a CPC1988 is in the "off" state, its optical control input is connected to ground by means of the Maxim multiplexer which prevents unintentional switch-on. To protect the CPC1988 switches from impermissibly high voltage peaks, a SMAJ440CA suppressor diode is connected in series.

The received signals of the 32 ultrasonic transducers can be connected to the input amplifier via four 8-channel Maxim multiswitches (MAX4598). Any switch positions are possible. To protect the multiswitches from high voltages (especially the transmit voltage), diode limiters are connected in series.

The individual transducer can be connected to the multiplexer via BNC connectors. On the back there is also a USB interface for connection to an external PC as well as a mains plug with switch. LEDs on the front of the housing indicate the current operating status of the system.

Position detection is carried out with the trakSTAR 2 system from Ascension Inc. The electromagnetic method offers a simple method of determining both the position and orientation of an object in space. In electromagnetic tracking, a magnetic field is generated within 1 m^3. The objects to be measured are marked with tracking sensors. These sensors determine their position and position on the basis of the magnetic field lines in which they are located. Since up to 32 ultrasonic transducers cannot be equipped with sensors and the working range of the magnetic field generator is not sufficient to detect all positions from one location without errors, a new algorithm has been developed in which only 2 sensors are necessary, which are successively attached to two adjacent ultrasonic transducers and the position of the generator can be changed. The active surface of the first transducer defines the coordinate origin. All other positions are measured relative to this. However, the tomographic algorithms assume a two-dimensional problem, therefore the points are transformed into a best-fit plane. As an alternative to magnetic field tracking, optical position detection using Aruco markers was developed.

Due to the inhomogeneity and scattering events in marble, there are a large number of paths and therefore also times of flight from the transmit to the receive transducer. As a result, the detect-ed sound wave is a superposition of all incoming sound waves and therefore very long in time. For tomographic reconstruction, however, only the linear propagation is of interest as an input parameter. In a first approximation it is assumed that this wave also arrives at the receiver first. Therefore it is necessary to detect the beginning of the recorded signals. One way of detection is the cross correlation method. The correlation result describes the similarity of two signals. A measured transmission signal through water is used as the reference signal (kernel). The spectrally filtered signal is correlated with the kernel, the envelope is calculated and its first peak above a threshold value is determined. The detection of the signal beginning now results from the detection of the peak under consideration of the size of the correlation kernel.

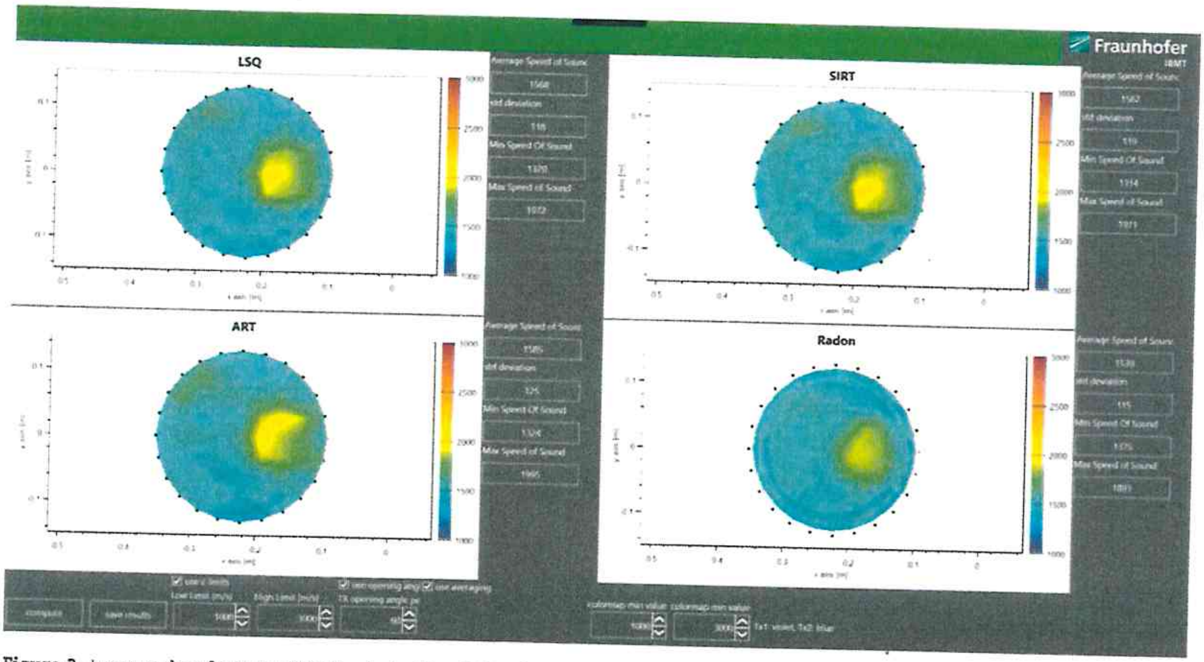

Figure 3: tomography of a water filled bucked with a POM cylinder.

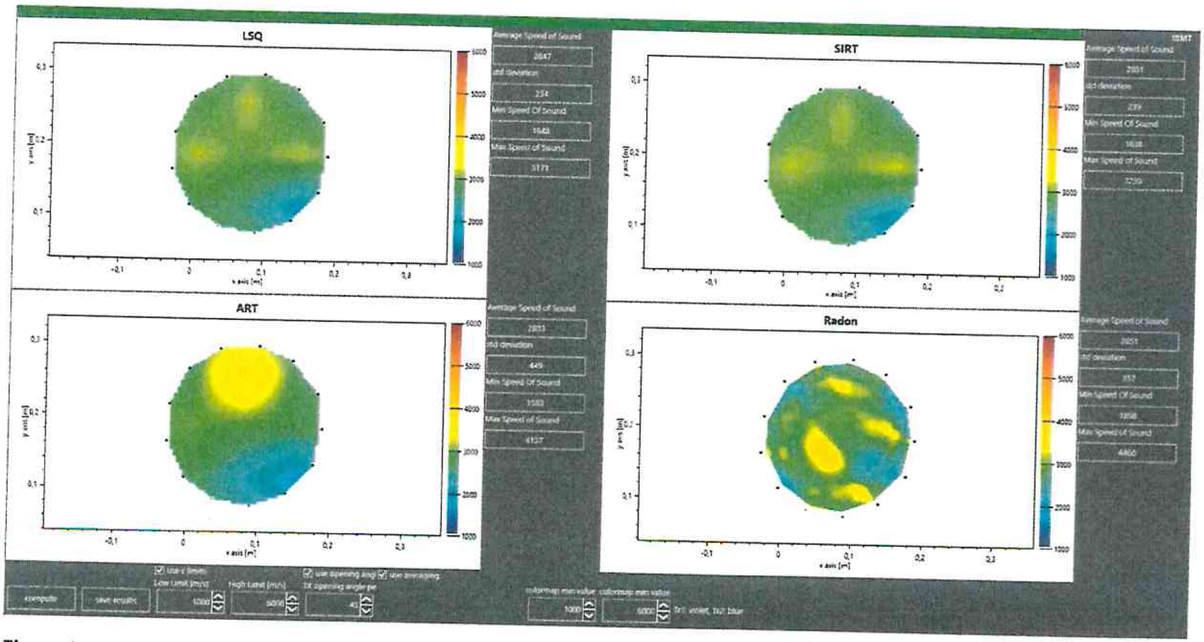

Figure 4: tompgraphy of an artifically aged marble cylinder.

The software of the system offers the possibility to calculate tomographies by algebraic reconstruction technique (ART), simultaneous iterative reconstruction technique (SIRT), Kaczmarz method, and inverse radon transformation of the velocities calculated by converter positions and times of flight.

Measurements

The new ultrasound system was first tested in the laboratory on so-called ultrasound phantoms. The first phantom was a cylindrical bucket filled with water in which a rod (Ø = 90 mm) made of polyoxymethylene (POM) was placed. Tomography was performed with 24 ultrasound transducers.

Figure 3 shows the result of the evaluation. The rod made of POM is clearly visible as a yellow area. The sound velocity in water was calculated with approx. 1.500 m/s and the sound velocity in POM with approx. 1.900 m/s was calculated correctly. The second phantom was a cylinder made of Carrara marble which was artificially aged. The cylinder was then heated to 150 °C and thrown into cold water. Thus, the average speed of sound could be reduced to approx. 3.200 m/s. Figure 4 shows the results of the evaluation. These correspond well with the expected values.

After successful measurements in the laboratory, the system was tested on the columns (Ø = 550 mm) of the Marmorpalais in Potsdam (see Figure 2). These are heavily weathered and show cracks, some of which have been filled.

Figure 5 shows the found structure of the marble. Although signals could be received at this object, they had large interference components. An automatic detection of the signal beginnings and thus an evaluation of tomography was not possible. The performance limit of the system was reached because of the strong fissuring of the stone.

Discussion

The measurements on the ultrasound phantoms prove the principle functionality of the new ultrasound system in the creation of tomography on stone. The positioning of the ultrasonic transducers with the holding system takes approx. 30 min. and the recording of the positions approx. 10 min. The actual measurements and the calculation of the tomography take approx. 20 min. with max. 32 transducers. The determination of a tomography is thus easily possible within one hour. The transmission voltage of 1,000 Vpp at 9 mm aperture of the transducers is not sufficient to receive evaluable signals in case of strongly weathered and fissured marble. In addition in all cases, the high transmit voltage on the multiplexer generates a coupling to the receive channels. The resulting signals allows a reliable measurement only from 150 mm marble thickness.

Conclusion

The principle feasibility and the associated time saving could be demonstrated. However, a device that can be used practically requires the revision of the multiplexer and the electronics. As mentioned before, the high transmitt voltage generates a coupling to the receive channels and therefore the begin of the signal is difficult to define and structures thinner than 150 mm cannot be examined. This problem can be solved by a new layout which carefully separates the transmit and the receive parts of the electronic and their electrical grounding.

Furthermore, the holding system of the transducers

Figure 5: typical structure of the marble columns of the Marmorpalais in Potsdam.

should be optimized to allow a strong and secure mounting of the transducers on the marble surface. The existing system software has many useful features and is easyly to handle. Together with an optimized hardware, the system could accelerate the tomography of stone made cultural heritage.

Acknowledgements

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