INVESTIGATING CHIME BAR VIBRATIONS USING HIGH-SPEED STEREOPHOTOGRAMMETRY

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ABSTRACT

Stereophotogrammetry is an optical distance measurement method. Using digital image correlation, the 3D coordinates of control points on a surface are calculated from a stereocamera recording. The use of highspeed cameras allows to obtain time resolved displacement data suitable for structural vibration analysis. The technique appears to be attractive to study musical instruments under realistic performance conditions: The measurement is non-invasive and both rigid-body motion as well as acoustically relevant vibrations are obtained from one video sequence. However, the spatial resolution is far less compared to interferometric measurement methods, and depends strongly on the specific measurement setup, namely, the size of the measurement window, the distance from the measurement object, and the lighting situation. This contribution presents a feasibility study on a Double Bass Chime Bar in A ($f_0 = 110$ Hz) and discusses potential fields of use of the method in musical acoustics research.

1. INTRODUCTION

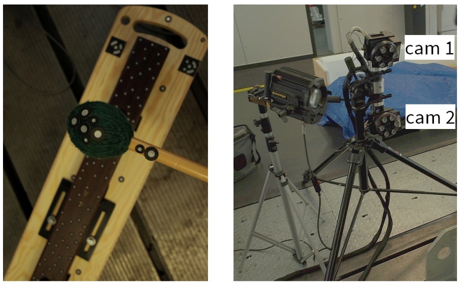
Experimental vibrational analysis of musical instruments is mostly carried out using a defined excitation, i.e. a hammer or a shaker. After a series of sequential single point measurements with an accelerometer or laservibrometer, modal shapes, frequencies and damping can be estimated. Most mechanical musical instruments have been studied already in this fashion [1].
However, the vibration measurement on musical instruments *under playing conditions* is challenging: On the one hand, the realistic musical excitation by a musician is very difficult to measure without disturbance. On the other hand, the instrument usually is moved during performance and mounted sensors would not only disturb the structure, but also the musician. One walkaround is to use artificial excitation mechanisms, such as artificial hammering, plucking [2], bowing [3] machines, that assure musician-like but well defined and reproducible excitation. A disadvantage of this approach is, that transient behaviour along with artistic articulation are not measurable. To overcome these limitations and measure the vibrations of musical instruments during musical performance, contact-free, time- and space resolved simultaneous measurements of many points on the musical instrument structure are necessary. These requirements are in principal met with Highspeed Stereophotogrammetry (HSSP).
With this method, the 3-D coordinates of arbitrary control points on the body surface can be calculated from pixel data of two digital cameras, which face the object under certain angles. The spatial resolution and accuracy achievable with this image correlation based method is scarce compared to interferometrical methods. The technical specifications of the high-speed cameras limit the measurement: Space- and time resolution, as well as measurement time depend on each other and are constrained by the camera sensor size, the distance between the two cameras, and between cameras and measurement object, the size of the measurement plane, the speed and size of the buffer storage and the lighting conditions. Thus, the feasability of the method has to be identified with respect to the specific measurement task. HSSP has recently been used successfully for applications in vibration analysis of structures with strong rigid body movement, such as rotor blades [4, 5, 6].
To the knowlegde of the authors, very few studies have been carried out that used HSSP to monitor acoustically relevant vibrations (e.g. [7], [8]).

2. MATERIAL AND METHODS

To study the feasability of HSSP in vibrational analysis of musical instruments, the chime bar is well suited due to its plane rectangular surface. Furthermore, its vibrational characteristics have been studied in great detail (e.g. [9]).

2.1. Measurement setup and data acquisition

As a preparation prior to the optical measurement small circular stickers of a reto-reflecting material are tacked in an irregular pattern onto the surface to be measured (Figure 1 a).
The HSSP measurement system PONTOS (Fa. GOM, Braunschweig, Germany) was used in the measurement. Two high-speed cameras are mounted on a rail, such that their angle of cut is 25 degrees on the measurement surface (Figure 1 b). Due to buffer limitations the measurement time depends on the frame rate. The measurement time can be prolonged by reading fractions of the full sensor per shot.
For this feasability study, the framerate was set at 2 kHz which is the maximum framerate of the system. The image size was set to 256x1024 pixel, which is a quarter of the full sensor size. With these settings, 2.5 s could be recorded. For times of exposure smaller than 0.5 milliseconds, a powerful light source has to be used. The PONTOS system comprises six LED flashes around each camera lense, triggered with the camera shutter.
The surface of the Chime Bar has a length of 500 mm and a width of 50 mm. The distance between the cameras and the bar surface was 0.75 m. Once camera and measurement object is fixed, the calibration procedure is done by taking a sequence of pictures from a calibration plate under different tilt angles. The warping of the calibration pattern in the sensor images is then evaluated to span a measurement volume. Inside this volume 3 D cartesian coordinates can be assigned to any measurement point on the surface. Subpixel accuracy is achieved by an image postprocessing algorithm, that detects the centers of the ellipses that the circular reflecting stickers produce on the two camera sensors. The raw data from the HSSP measurement is a point cloud in x, y and z for each frame of the video recording.



a) b)

Figure 1: Setup for HSSP measurements on a Chime Bar
a) Retoreflecting stickers mark the measurement points on mallet and chimebar surface.
b) Stereophotogrammetry system PONTOS (Fa. GOM) Measurements were carried out at ILK (Technische Unversität Dresden)

2.2. Postprocessing of the raw data

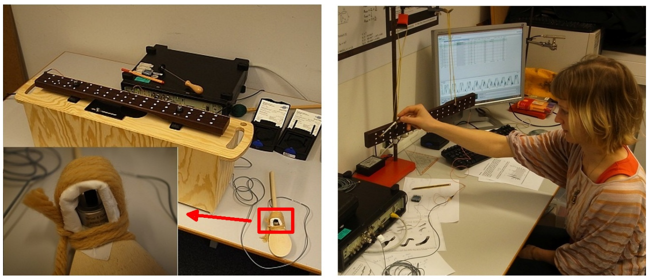
The Chime Bar is mounted on loosely to a resonator box by two pins perpendicular to its surface. The pins are padded with a soft rubber and felt such that the rigid body motion of the bar can have strong components of what would be called "heaving" and "rolling" motions in a ship.
To analyze the acoustically relevant bending motions of the bar, the rigid body motion was determined frame by frame principal coordinate analysis. Projecting the raw data on the time dependent principal coordinate system yielded new coordinates x', y' und z' of the measurement points. These were interpolated on a rectangular grid $(x'_{i,j}|y'_{i,j})$. The result of the post-processing is for discrete, equidistant measurement points i, j, the deflection of the Chime Bar $z'_{i,j}(t)$ perpendicular to its surface. The post-processing of the HSSP raw data was done using MATLAB.
The (freely choosable) resolution of the measurement grid was $\Delta x' = 36$ mm, $i = 1..12$; und $\Delta y' = 10$ mm, $j = 1..4$.

2.3. Comparison Measurements

For comparison purposes measurements with an accelerometer have been carried out on the same Chime Bar at various excitation levels. After integrating the measurement results twice they can be compared with the processed optical displacement data. Two experiments have been carried out: First, in a typical musical situation as in the HSSP measurement. A wooden stick with a force sensor wrapped in tissue and wool served as a mallet to determine typical excitation forces at various musical dynamic levels (Figure 2 a). Second, a classical modal analysis experiment of the bar only. The Chime Bar was unmounted from the resonator box and excited at several points by an impact hammer and the vibration was recorded by an accelerometer in a fixed position at the edge (Figure 2 b). When comparing modal analysis results, this second measurement will be referred to as EMA.

2.4. Modal Analysis

Fron the postprocessed optical displacement data $z'_{i,j}(t)$ of the Chime Bar a modal analysis was carried out using Operational Modal Analysis (OMA). This is a stochastic system identification method which bases on a singular value decomposition of a matrix of concatenated spectral density vectors representing system responses measured simultaneously at several measurement points on the structure. Modal shapes, frequencies and damping values can be determined without explicit knowledge



a) b)

Figure 2: Comparison measurements with an accelerometer a) excitation with a modified mallet, b) roving hammer modal testing experiment.

of the excitation function [10]. This is useful for the present HSSP experiment, where the Chime Bar is struck with a normal mallet and the excitation force is unknown. For the identification of modes, the curve-fit-frequency-domain algorithm (CFDD) implemented in the commercial software PULSE Labshop Type 7760, V 18.1 (Brüel&Kjær, Nærum, Denmark).
The combination of applying this modal analysis method on high-speed stereophotogrammetry data will be called HSSP-OMA in the following.

3. RESULTS

The advantage of the HSSP-method is that the displacements at various points are measured simultaneously. When looking at single point measurements, however, the limited dynamic range compared to contact-free interferometrical methods is obvious. Figure 3 shows displacement levels and decay curves for two different excitation locations of the Chime Bar, the sensor was mounted near an edge of the bar. The data are shown in Figure 3, where the suppression of the $4^t h$ partial when striking the bar in the middle (L/2) and the dampening effect of the acoustical resonator on the bar vibrations are clearly visible
The displacement magnitudes in the Chime Bar range from millimeters at the fundamental frequency to less then a micrometer above 1 kHz when playing *forte*, and down to a few nanometers when playing *pianissimo* (Figure 4). That is well below the noise floor of the HSSP-measurement. For the setup described above, the noisefloor in z' was 6.8 ± 1.2 micrometer RMS (mean and standard deviation, averaged over the 48 grid points).
For comparison, typical displacements in modal hammer measurement from the EMA experiment are shown in Figure 4, where the Chime Bar was disconnected from the resonator.
The OMA takes advantage of the fact, that all displacements are measured at the same time. Despite the limited signal to noise ratio, this feasability study on HSSP-OMA shows an excellent agreement in the modal frequencies as compared to the classical EMA method. However, the limitations of the sampling rate do not appear to be important given the low spatial resolution in this measurement setup.
Table 1 shows a comparison of EMA and HSSP-OMA modal analysis results. The indices (n,m) in the first column describe the modal shape in terms of the number of nodal lines perpendicular (n) and parallel (m) to the wood fiber direction of the bar. The acoustically relevant partials of the Chime Bar in the range $f < f_s/2$ are the fundamental $f_0 = 109.3$ Hz and the fourth partial at $f_4 = 438.2$ Hz $\approx 4\, f_0$ (see Table 1). At these frequencies, the Chime Bar performs bending motions with two

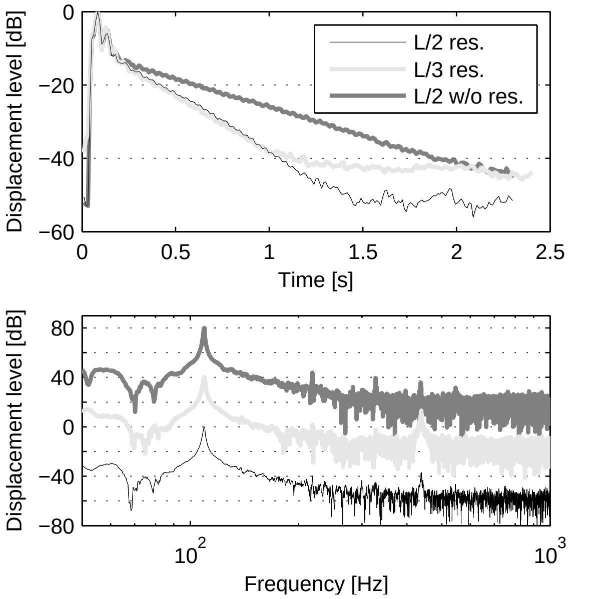


Figure 3: Displacement levels for three strikes in *mezzoforte* on a Chime Bar as measured with HSSP. The striking position were approx. L/2 and L/3 measured from the edge, the measurement point is near the edge of the bar. For the third strike (L/2 w/o res.), the resonator hole was covered with a sheet of paper. Curves are shifted vertically for better readability.

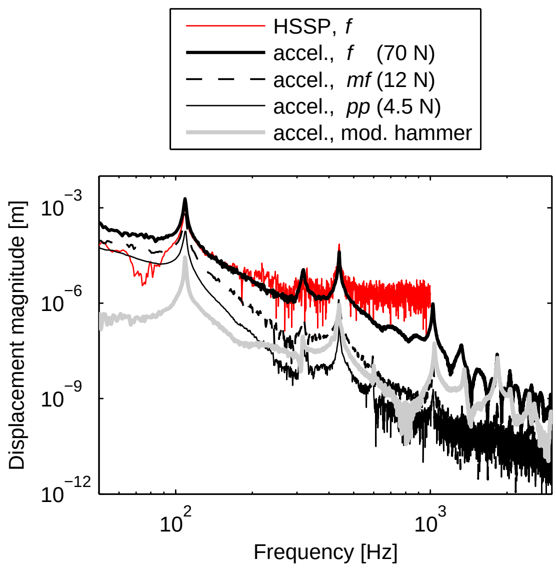


Figure 4: Displacement magnitudes of the Chime Bar directly measured with HSSP and integrated from accelerometer measurements. The bar is struck with a normal mallet (HSSP), a modified mallet equipped with force sensor, and a modal hammer. Values in brackets are the peak forces measured with modified mallet.

and three nodal lines, respectively, perpendicular to the longitudinal axis of the bar. With a low signal-to-noise ratio of about 16 dB at the fourth partial, the (3,0) modal shape still is clearly detected from HSSP-OMA (Figure 5). The occurence of the (1,1) torsional mode depends on the offset of the striking position with respect to the longitudinal center line. The fact that no modal shape could be identified with the OMA algorithm is possibly due to a centered strike. The signal-to-noise ratio of the respective (1,1) peak around 320 Hz is only slightly lower than that of the (3,0) peak around 440 Hz (see Figure 5). The mould on the bottom side of the bar is cutted by the instrument makers to tune these two modes to a harmonic frequency ratio [11]. Further, also the tenth partial can be tuned to an integer ratio with the fundamental. In the present study we find $f_{10} = 1038$ Hz $\approx 9.5\, f_0$ only in the EMA measurement. It is possible, that the mass added to the bar by the accelerometer in this measurement has lowered this modal frequency.

In contrast to the classical roving hammer method (EMA) are the results of the OMA not based on a lab experiment, but stem from a fully contact-free monitoring of the bar vibrations under realistic playing conditions. While the EMA lab test will reveal all possible modal shapes, the HSSP-OMA method only detects the relevant vibrational modes that are excited when playing the instrument. From the results it can be seen, that the (1,1) torsional mode and the (2,0) lateral mode (column 3 and 5 in Table 1) not only are inefficient radiators [11], but also are excited weakly in a normal musical excitation. Aside from the modal shapes, the OMA also reveals relative amplitudes of the modes and their time decay (not shown here).

4. OUTLOOK

With the Chime Bar an example for a simple musical instrument structure has been chosen intentionally for this feasibility study. Not only the geometry can be measured easily, also

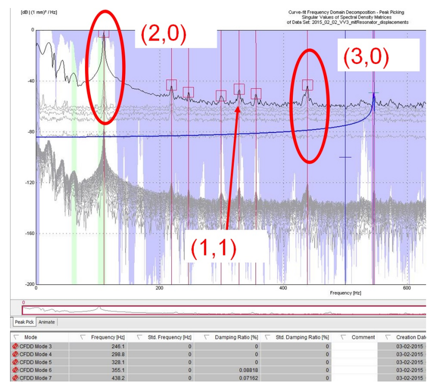


Figure 5: Screenshot of the Modal Analysis (OMA) on high-speed stereophotogrammetry data of a struck Chime Bar using the Brüel&Kjær s software PULSE Labshop.

the impulsive manner in which it is played approaches a broadband excitation, an assumption the operational modal analysis is based on.

Potential uses in musical acoustics depend critically upon the size of the structure and the displacement magnitudes at the vibrations of interest. The noise-floor of HSSP measurement is determined by the size of the measuring field and the minimum possible camera distance. With appropriate lenses, spatial resolutions in the nanometer range are possible [13]. To detect eigenfrequencies in musical instrument structures that are driven quasi-periodically, the harmonic components of the excitation must be treated separately. Implementations for this approach are reported in the literature [12]. HSSP is to the authors knowlegde the only method that allows for contact-free simultanenous measurements of fully transient structural vibrations

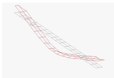
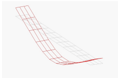
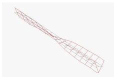
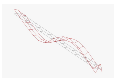
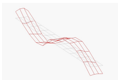
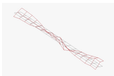
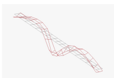
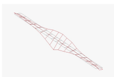
	EMA Impact hammer + Accelerometer	OMA Mallet + Photogrammetry	Literature [9]
(2,0) f_0 [Hz] f_0 / f_{nom}[Cent] ζ [%]	 109,2 -13 0,21	 109,3 -11 0,50	
(1,1) f [Hz] f/f_0 [-] ζ [%]	 315,2 2,89 0,45	*not found*	2,48
(3,0) f [Hz] f/f_0 [-] ζ [%]	 438,9 4,02 0,24	 438,2 4,01 0,07	4,03
(2,0)* f [Hz] f/f_0 [-] ζ [%]	 599,0 5,49 0,26	*not found*	7,01
(4,0) f [Hz] f/f_0 [-] ζ [%]	 1038 9,50 0,28	$f > f_{\mathrm{Nyquist}}$	10,70
(2,1) f [Hz] f/f_0 [-] ζ [%]	 1361 12,46 0,45	$f > f_{\mathrm{Nyquist}}$	11,09

Table 1: Modal Analysis of a Chime Bar. Comparison of results of the photogrammetric measurements (column 3) with the roving hammer measurements (column 2) and literature data (column 4). EMA: experimental modal analyis, OMA: operational modal analysis, * lateral mode

at musical instruments under playing conditions. The combination HSSP-OMA is especially interesting because it allows for the characterisation of the instrument while interacting with the player in a mostly disturbance-free manner during performance, rather than studying only the instrument itself under lab conditions. This can be a basis to study performance differences between musicians playing the same instrument, and may be useful to validate complex physical models that are used in digital sound synthesis with great success [14]. If the drawback of the relatively low spatial resolution in the range of micrometers can be overcome, HSSP-OMA can be a very useful measurement technique to investigate in detail the relationships between the construction of musical instruments, their excitation and finally their produced sounds.

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