Audio Engineering Society

Convention Paper

Presented at the 126th Convention
2009 May 7–10 Munich, Germany

Measuring Transient Structure-Borne Sound in Musical Instruments – Proposal and First Results from a Laser Intensity Measurement Setup

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ABSTRACT

The proposal for this new measurement setup is motivated by curiosity in transients propagating across arched tops of violins. Understanding the impact of edge construction on transient wave reflection back to the top of a violin or on conduction into the rib requires single-shot recordings possibly without statistical processing. Signal-to-noise ratio should be high although mechanical amplitudes at distinct locations on the structure surface are in the range of a few micrometers only. In the proposed setup, the intensity of a laser beam is directly measured after passing a screen attached to the device under test. The signal-to-noise ratio achieved for one micrometer transients in single-shot recordings is significantly more than 60 dB.

1. INTRODUCTION

The paper proposes an alternative laser-based measurement setup for measuring individual transients of small amplitude in structures of little weight. For instance, in musical instruments such as violins, the spruce top excites only few micrometers and weighs around 60 grams. Some areas of interest weigh less than ten grams. The authors are interested in transients that travel across the top to the edges where they will be partially reflected back to the top and partially travel further through the rib to the bottom. Whereas modal analysis usually only spot the few frequencies of low-impedance steady-state harmonic vibrations in a system, the transients tell the wider story from excitation to sound radiation especially in the frequency regions between the modes. Another aspect of sound radiation is the question of energy. As a transient travels towards the edges and the rib, the steadily increasing stiffness might well reduce the amplitude of that transient but not necessarily its energy. The question of sound radiation may well become a question of where the energy is hosted in the system, if we are ready to accept the general context of 1/f damped systems. So where are the transients?

1.1. Requirements

Requirements arise from our intention to measure transients of little amplitude in structures of little weight:

a) Any sensory device should have almost no mass. Contact-less measurement would be perfect.

b) The measurement system should not hinder the free radiation of the device under test. Early reflections would otherwise feedback into the system.

c) The measurement must be focussed. We want to measure with a local resolution in the range of millimeters.

d) The measurement should still deliver a useful signal-to-noise ratio when amplitudes are very small. Whereas sound studios usually require ratios of 100dB and more, we would be satisfied to achieve 50 to 70 dB, since our questions are related to energy and radiation.

e) Single-shot recordings are preferable for some scientific questions.

On realizing a measurement setup, further boundary conditions arise:

f) Ambient noise limits, including conduction in building structures, must obey requirement d) as well.

g) Structure-borne conduction between the device under test and the measurement set-up with its exciter mechanics should also follow the signal-to-noise requirement under d).

h) Cost should be low.

1.2. A Brief Review on Measurement System Options

As we screen the state of the art technology options, we find that most of them fail in satisfying all requirements. Accelerometer sensors usually weigh a few grams and are far too heavy. Microphones satisfy almost all requirements but not really requirement c). Microphone arrays seem eligible for the task especially with the given progress on near-field acoustics [1]. But even when organized in an array, a microphone will always capture sound pressure or a gradient of sound pressure. Whatever radiation characteristic of the microphone is given, it will always capture the dominant pressure. Backwards propagation from captured sound pressure to structure surface excitation is always frequency-specific and at the same time superimposed by dominant contributions from other radiating regions. A movie obtained from a microphone array will first of all show propagating pressure waves that are around. In our case, the sound radiated at the violin bridge is dominant against the sound radiated in other regions, especially in the distant and stiff region of our violin top edges. So for the desired edge observation the starting position in terms of signal-to-noise ratio is around -20 dB to -30 dB, leaving the challenge of achieving the missing 70 dB to 100 dB by intelligent back propagation. Most of the systems based on laser interferometry have the same problem of achieving a good signal-to-noise ratio. Even when surface-reflection is optimized, the systems tend to require repeated excitation and statistical post-processing to achieve significant signal-to-noise ratios, especially when amplitudes are very small. Apart from the technical challenge, systems based on laser interferometer principles [2], such as Electronic Speckle

Pattern Interferometry, (ESPI) [3] or Low Coherence Speckle Interferometry (LCSI) [4] are usually far too expensive.

2. MEASUREMENT PRINCIPEL AND ISSUES

Other than the commonly employed phase measurements on laser beams, the proposed set-up gains information from the beam intensity. A laser beam will be directly captured by a photo sensor, without filters, mirrors or other reflections in between. On the device under test, a screen is fixed. This screen acts as an aperture and effectively translates excitation into beam width variation and therefore into intensity variation, see Figure 1.

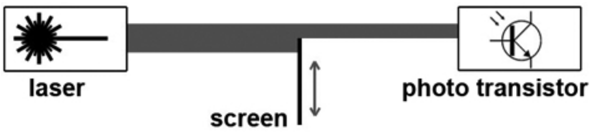

Figure 1: laser beam passing a screen; intensity captured by phototransistor

The main objections against this simple approach are (i) unknown scaling from excitation to beam intensity, the stationary transfer function, including unknown optical diffraction at the screen, (ii) unknown dynamical transfer function, (iii) stability over time and (iv) stability of the optical axis against the environment and against the vibration of the excited device under test. Problems (i) to (iii) are addressed by a linearization procedure prior to measurements. Issue (iv) is addressed by a specifically designed measurement table.

3. MEASUREMENT SETUP

3.1. Measurement Table

This section describes the properties of a first prototype system in a research environment. We considered existing optical tables as limited when it comes to structure-borne conduction and the task to isolate three distinct subsystems against each other and against the environment. In addition to the requirement of damping between these sections comes the requirement of mechanical stability between these sections as we measure excitation in the range of few micrometers and less. The subsystems are: (i) a stationary optical section with two distant points, (ii) a vibrating device under test and (iii) an exciter section.

In our prototype solution we address this issue of mutual damping and stability by using two tables on top of a carrier table. The carrier table is a 80 cm x 80 cm x 80 cm large block, weighs 1.2 tons and consists of concrete. The carrier stands on vibration damping feet and effectively damps the entire system against the environment. This block carries a 170 kg ring table for the optical line. It also carries a 120 kg table for the device under test which is located within the ring table. Both top tables are isolated against the carrier table by a damping 4 mm polyurethane layer. The closely related subsystems, optical line and device under test, are therefore mechanically well defined and sufficiently stable. The third subsystem, the exciter, can be employed from outside the entire system, or, when necessary, can be fixed at the carrier block. The mutual damping factor between the subsystems has been measured and is minimum 50 dB over the interested audio frequency range.

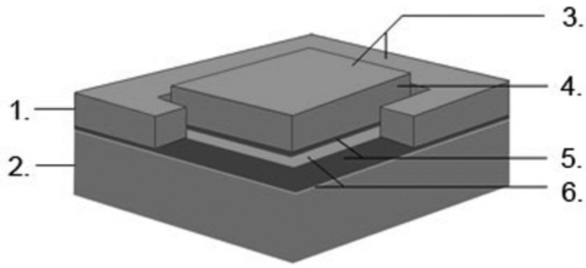

Figure 2: measurement table (section), 1. outer concrete ring, 2. concrete carrier block, 3. epoxy resin layer, 4. inner concrete table, 5. epoxy resin layer, 6. PUR layer

3.2. Optical Path and Mechanical Components

The optical signal chain begins with a non-pulsed low-budget 5mW 655nm laser diode (IMDL-650-5-I-56). The beam is focussed by a low-cost 4-lenses collimator. The circular beam then passes an aluminium screen which is mounted on top of the surface of the structure under investigation. The screen is a 2 mm x 2 mm piece of commercially available aluminium foil. It is typically 13 micrometer thin and weighs significantly less than 0.01 grams. The screen will generally shadow a good fraction of the laser beam. Focussing and mechanical adjustments are no issues for the measurement principle, as the system will comfortably work with any fraction between 10% and 90% of the laser beam. At the end of the optical path the +/-10° lens of a low-cost photo transistor (BPW14) will collect the arriving beam. Mechanical adjustments are, however, an issue for the necessary upfront linearization procedure. In order to obtain the stationary transfer function the optical subsystem will be stepwise moved against the device under test subsystem. Both ends of the optical beam are mechanically fixed on x/y linear tables with an adjustment precision of one micrometer (2 x 2 x M-SDS25).

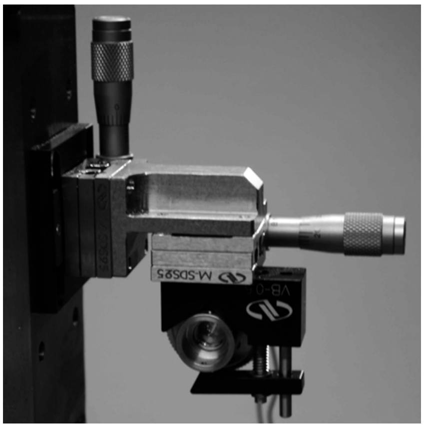

Figure 3: collimator on x/y linear tables

3.3. Electrical Signal Chain

The electrical signal chain begins with the photo transistor which is driven at the lower end of its sensitivity due to the relatively high intensity of the laser beam. The analog signal is simply converted to low impedance with a control circuit driving the emitter-base junction. An optional AC coupling allows the compensation of drifts. The signal can be A/D converted via commercial sound cards. For reproducible, scientific measurements we used a DATAREC4 DIC6 system.

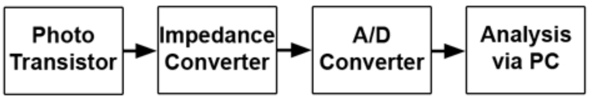

Figure 4: electrical signal chain

4. MEASUREMENTS

4.1. Measurement Procedure and Experience

Prior to measurements, the stationary transfer function from the mechanical excitation to the analog signal will be obtained in a semi-automated procedure. Mechanical adjustments are done manually, requesting a total time of 20 minutes for a 20 step curve. Transfer functions are usually well repeatable. Figure 5 shows a typical transfer function which will cover both, the non-linear relation between excitation and beam intensity and the uncertainties due to diffraction at the screen edge or even due to possible additional reflections in the system setup. The three individual curves were taken in three different measurement sessions on a single day. From these curves, one may wish to choose an advantageous operating area.

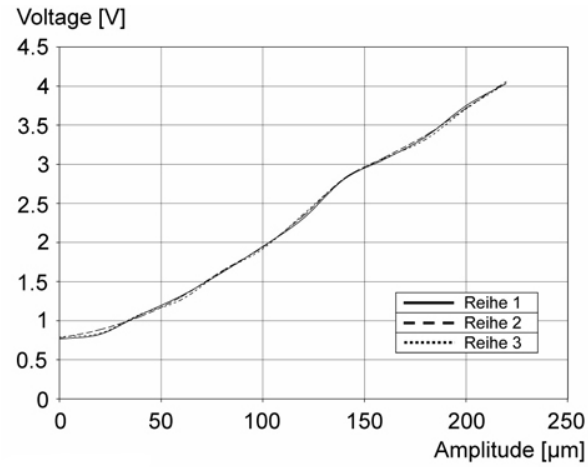

Figure 5: typical stationary transfer function from the mechanical excitation to the analog signal

After measuring the device under test, data will be scaled according to the stationary transfer function. To share some experience with this procedure, the prior measurement requires time and concentration, as well as documentation. Therefore, in the engineering workflow, a user will think twice before proceeding to the next measurement coordinate on a given structure surface. Furthermore, transfer functions are likely to drift over days. Any active change on the optical path will significantly change the transfer function, requesting new upfront measurements.

4.2. Dynamical Transfer Function

There are two limiting factors along the optical and electrical chain. One is clearly the stability of the optical screen and the other is the electrical circuit. In terms of the optical screen it is desirable that the translation from structure surface excitation to beam width variation is independent from frequency, at least for the audio frequency band. In this prototype setup we trust that the optical screen remains stiff for frequencies below the lowest frequency of possible modes in the small aluminium screen. The screen can analytically be considered as simply supported bar or as simply supported plates, following the nomenclature of Fletcher and Rossing [5]. Considering all optional analyses, the screen should be supported on the sides to obtain stiffness up to roughly 20 kHz. With a small guard folded at both sides of the aluminium screen together with the bottom guard, the screen can be considered as a plate which is simply supported at three edges.

The photo transistor easily works up to the 100 kHz range and the electrical circuit is designed to provide a bandwidth well beyond 40 kHz. The dynamical performance of the electrical chain is also limited by the properties of the A/D converter.

A measurement of the transfer function across the entire optical and electrical chain has not been done. This would require existence of an electro-acoustical driver with known transfer function in the audio frequency range, not from electrical to far-field acoustical properties, but from electrical to mechanical excitation at a distinct location on a membrane. There is no such data. Alternatively, a pure mechanical exciter could be developed with forced excitation properties over frequency.

5. RESULTS

One of the major results is that mechanical vibrations of little amplitude are well measurable with this intensity method. Figure 6 shows the spectrum of a harmonic test signal with a frequency of 1 kHz. The signal has been captured from the surface of a 1 cm piezo buzzer. The peak amplitude was close to 1 μm, and the signal-to-noise ratio is well beyond 65 dB across the audio frequency range.

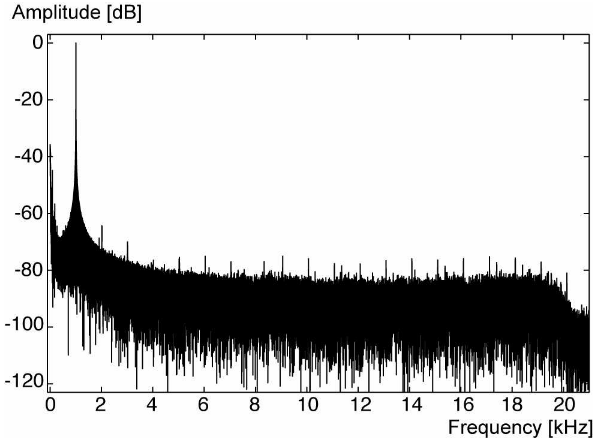

Figure 6: harmonic test signal at 1 kHz – signal-to-noise ratio over frequency

Figure 7 gives an example of signal quality for a plugged string on a violin. The signal is taken from the violin top and reveals expectable details.

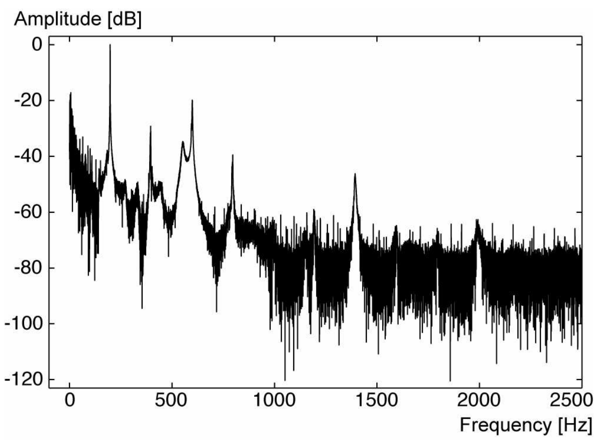

Figure 7: exemplary signal quality – plugged violin string measured at the top

Figure 8 shows the time structure of an impulse on a linear and on a logarithmic scale. Again, the signal is taken from the top of a violin and the signal-to-noise ratio is clearly beyond 65 dB. The quality of the signal can be listened to and is well reaching the quality of a microphone. Sound examples from ten positions on the top of a 1975 E. A. Roth violin can be downloaded and listened to under [6].

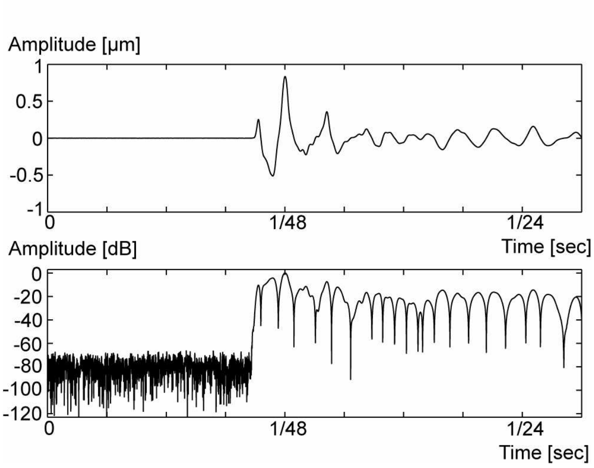

Figure 8: transient impulse on a violin – top: excitation over time, and bottom: same signal on a logarithmic scale

Transients with only one micrometer peak amplitude can be recorded in a single-shot fashion without the need for repetitions and for statistical averaging. There is enough signal intensity to stay well beyond noise. The related signal-to-noise level is 65 dB and more, and the signal reveals the expected very detailed structures.

6. CAPABILITIES AND LIMITS

This contribution brings up the idea of direct laser intensity measurement and it would be unfair to compare the presented prototype with well developed and expensive laser interferometry systems. A few general capabilities and limits are however already obvious and clear even in this early state of development.

A major capability is that the measurement principle allows for capturing high resolution signals. The signal starts with a very good power budget and the signal will stay well beyond noise even when amplitudes of surface excitation are very small. This also allows single-shot recordings of transients. This capability is interesting for all researchers who want to look closer into the generation process behind sounds or noise. Phase-based systems, on the contrary, will usually employ statistical post-processing to gain an acceptable signal-to-noise ratio, effectively loosing sight of the original source.

A limiting factor, on the other hand, is the vulnerability of the intensity-based working principle. As known from telecommunications and from experience on modulation systems phase-based systems prove to be more robust than intensity-based systems. Most of the vulnerability issues in the presented prototype are solved with the solid measurement table which is fine in stationary research environments.

Another limiting factor for surface measurements is that access to the investigated structure must always allow a direct beam. The system is not mobile. And the measurable excitation ranges from micrometers to millimeters.

To share some other work experience: the sensitivity of the system is so high, that even some unexpected microphone effects are to be kept in mind while measuring. Even the dust in the ambience will cause noise in the signal and ventilation of such air is measured as well.

7. CONCLUSIONS

We brought up the idea of direct laser intensity measurement for single-shot recordings of transients in light-weight structures. The presented prototype allows for such measurements at distinct positions and delivers respectable 65 dB signal-to-noise ration even when mechanical excitations are as small as one micrometer. Yet, the prototype is achieved on a very low budget. We outlined details of the system setup, listed employed components, mentioned recognized capabilities and limits and shared working experience in order to ease the translation into generic applications and other measurement scenarios. Next measurements with the prototype will focus on transient wave propagation from a violin’s top into the rib.

8. ACKNOWLEDGEMENTS

The authors wish to thank the German Federal Ministry of Education and Research for funding the research project on violin tone quality.

9. REFERENCES

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