Investigations on the directivity of string instruments using a bowing machine

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Abstract

String instruments exhibit a complex directivity which is not precisely referenced in the literature or often represented with a low spatial or frequency resolution. The goal of the bowing machine presented here is to provide a stable, realistic excitation for repeated captures of directivity measurements on string instruments. The instrument is excited by a bow mounted on a linear actuator which allows to obtain more reproducibility than measurements with real musicians and more precise results than by using other ways of excitation (rosin disc, shaker on the bridge, hammered or plucked strings...). By mounting the instrument together with the bowing machine on a 3D turntable we have studied the directivity of a violin in every direction with small angle steps. The setup has been used until now to study the directivity of a violin but could be adopted to investigate other string instruments.

Introduction

The nature of the musical instruments' directivity has been widely studied but is still today a subject of investigations. The radiation of loudspeakers and simple sound sources has been subject of detailed studies [1], but a remaining question is: how to obtain the 3D radiation of complex time varying sound sources such as string instruments? The question is legitimate today because several fields need the directivity of more complex sources and especially musical instruments: among challenges in virtual acoustics, determining precisely the directivity of musical instruments could be useful to build specialized rehearsal rooms for every instrument [2], to improve the acoustic or to isolate it better. We can imagine that in the next years, music schools or concert halls might be interested in improving the customers' experience in their room, by building better quality acoustic rooms. Having a 3D sound experiment is nowadays also sought-after by composers [3] for example. Concerts where the public is placed in the middle of the musicians illustrate well this increasing interest for 3D sound experience. In a period of strong development for virtual environments, especially for video games, it seems also necessary to be able to re-synthetize 3D scenes by matching the 3D sound experience with the visual experience.

Simple instruments and loudspeakers with symmetrical emission were already studied in all directions by measuring the directivity on one segment or plane and then extrapolate to every direction thanks to software like Matlab or Comsol [4], but for more complex instruments such as the violin these studies need to be done with another setup. In the last years some investigations on the 3D directivity [5] of the musical instruments have been started to complete the 2D studies [6] already done. It was possible because new recording technologies allow to push further these investigations.

Some experiments were done using a 3D array of microphones to represent the real time directivity (Fig. 1). These methods are complicated to set up, costly and the angle resolution of the directivity is low, typically between 20 and 45 degrees [5]. It has been realized especially for live performances and not reliable single measurements [7].

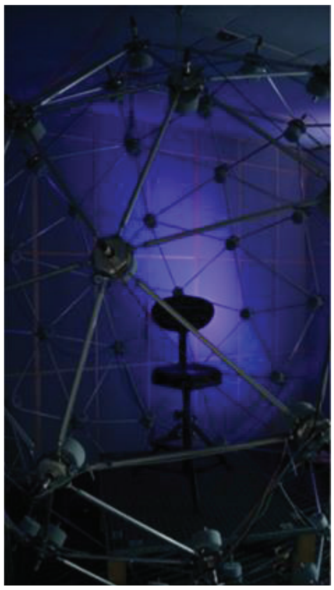

Figure 1. Microphone spherical array to record instruments' directivity, picture taken from [7] (Kunst Uni, Graz)

The only real 3D directivity measurements of complex musical instruments that can be found in the literature were made at TU Berlin and RWTH Aachen [8]. These measurements were done for every instrument with a spatial resolution of 20 degrees and using real musicians to excite the instruments. This already gives a good idea of the instruments' 3D directivity, but in order to be really stable and reproducible it would be interesting to provide an automated excitation to the instrument. An automated accurate excitation allows to measure sequentially and therefore the spatial resolution does not depend on an array of microphones.

Many methods have already been tested to provide controllable excitation to string instruments. For example, students of the Tufts University of Medford have used a rotating loop of bow hair to excite the strings (Fig. 2 left). This method is interesting because it is really close to the real bow conditions, the material in contact with the strings is the same as a bow and gravity has less effect on the machine than a real bow. However, the tension on the strings might be slightly different and difficult to control, and the loop has a punctual defect where the hair is tightened.

A recent development at HAW Hamburg was a height-compensated pendulum that uses its own weight to strike the strings [9] (Fig. 2 right). This setup is capable to control precisely the bow force and to study the slip-stick interaction between the bow and the strings. However, the pendulum supports have to be fixed and therefore the setup is essentially immobile.

Another method is a rosin disc scraping the strings [10]. This method using rotating discs of celluloid treated with rosin to strike the strings is interesting because it is easy to control the speed, the pressure and the gravity has almost no effect on the setup. However, the material used is different from a real bow.

Other methods allow to excite directly the bridge of the instrument, such as a shaker glued to the bridge [11], or a hammer hitting the bridge [12]. These methods are used because they are very convenient for automation, provide a broad band excitation and give an approximation of a real violin excitation, but the response of the instrument is of low SPL and not comparable to bow excitation.

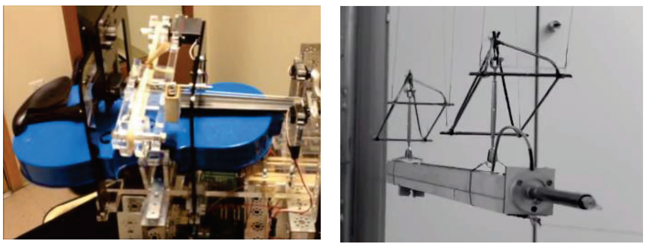

Figure 2. Tufts Robotic violin project (left) and cello bowing pendulum (right) [9]

The goal of this study is to create a repeatable setup allowing the 3D measurement of string instruments radiation pattern in playing conditions with a high angle resolution and as close as possible to the real condition of playing. That's why we chose to excite the instrument strings with a bow.

Description of the setup

Even if the bowing machine might be adaptable for different string instruments, it was at first built to study the directivity of the violin, for size reasons.

It is composed of a bow actuated by a linear stage. This bow actuator and the violin are fixed on a 3D turntable (Fig. 3) (ELF, Fouraudio, Germany). A fixed microphone or a dummy head is placed in front of the setup as the ELF rotates the violin in every direction. This configuration allows to take measurements with a high spatial resolution and to have a single microphone to record the signal, which is convenient for installation and for data processing.

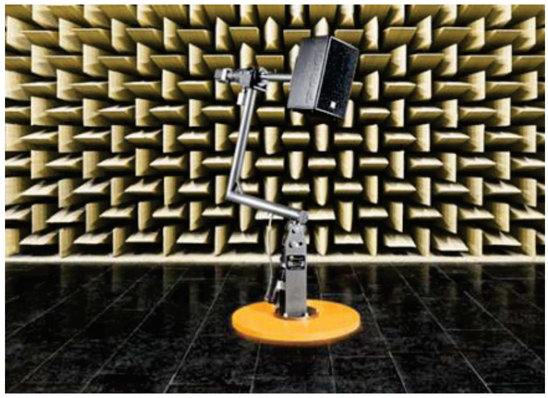

Figure 3. ELF 3D turntable from Fouraudio, photo taken by Thomas Streit, used with kind permission

The violin and the linear actuator in charge of the bow stroke are both fixed on an iron table, itself fixed on the head of the ELF.

The violin is clamped at the neck and the chin rest, where a musician usually holds it in order not to attenuate other vibrations of the instrument's body. The bow is held by a frame of aluminium tubes, fixed on the linear actuator carriage, chosen to be strong and stable enough to carry this charge (Fig. 4). The armature is fixed on the linear actuator through a wooden plate which has the role of an adaptor. The bow is fixed both at the screw near the frog and at the tip, to compensate the gravity effects on it. The armature was designed to allow the full bow stroke without being disturbed by the violin body and have a constant force while bowing the string along the bow length.

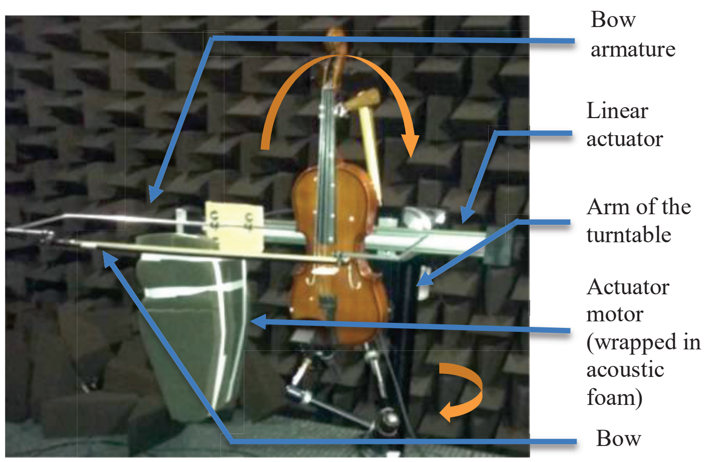

Figure 4. Violin and bowing machine mounted on the turntable

In order to capture only the direct sound of the instrument and avoid any reflexions of the room, the setup is placed in an anechoic room. The linear actuator, the ELF and the sound acquisition are all controlled through a Matlab script, from a computer outside of the room.

Parameters

The bow has a constant speed of up to 2,5 m/s, the force on the string has not been measured but it is assumed to be constant and reasonable in order to have a sound adjusted by ear approved by a professional string player. The bow can be adjusted to produce a fifth while striking two strings or to strike only one, here the A string. The acoustical centre of the violin was assumed to be around the bridge position and it is centred on both horizontal and vertical motors' axis of the ELF. The microphone has been placed at 1.50 m distance from the acoustical centre of the violin, at the same height, in the horizontal plane. The measurement was done with 3 degrees steps between each measurement. The motor's noise was reduced by wrapping it into acoustic foam.

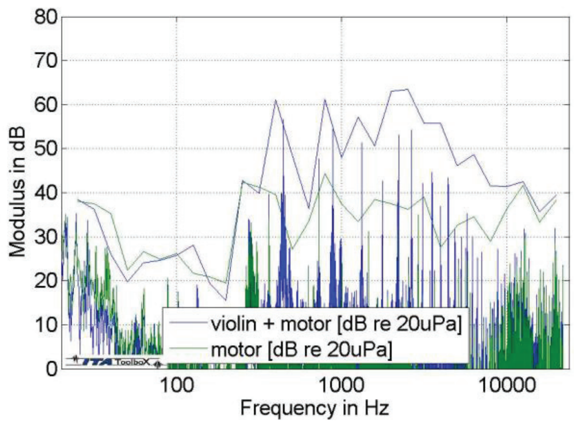

Figure 5. FFT and third octave spectra of the motor wrapped in foam, with (blue/violet) and without violin sound (green)

As we can see on Figure 5, the noise of the motor is some 20 dB below the violin signal in this experiment, from 500 Hz to 8000 Hz. It does not cover the whole violin frequency range but for our first experiment on the A string we can assume that we do not have problems with the motor noise.

Results obtained

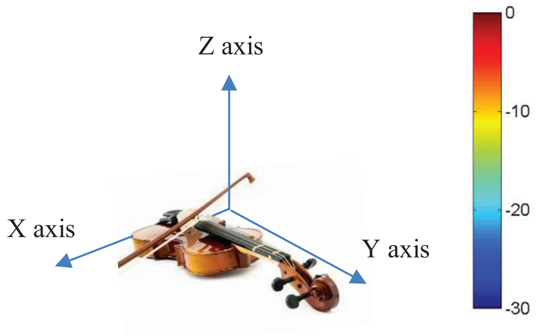

Figure 6. Orientation of the violin in the coordinate system of the result plots, with intensity color scale of the measurements

After some data processing to draw balloon plots, we obtained the results in Figure 7:

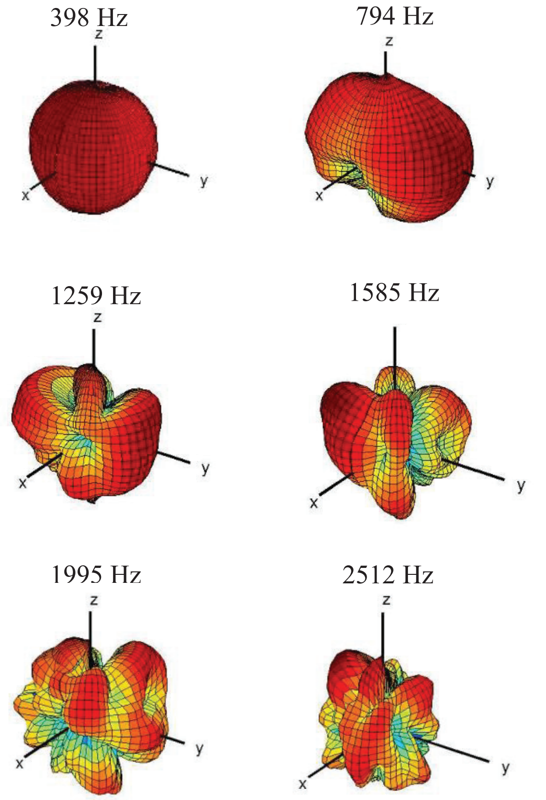

Figure 7. Directivity balloon plots of the violin for different frequency bands, obtained with the bowing machine

These plots were generated from third octave bands of the violin acoustic radiation spectrum at some frequencies. They do not represent radiation of eigenmodes for 2 reasons:

- Excitation of the violin is not a broadband excitation. As we are exciting only the A string, the emitted spectrum is sparse and potentially does not excite at the eigenmodes' frequencies.

- The system is not free; the oscillations are maintained by the bow which periodically provides and also attenuates energy in the system in order to have a constant sound.

On figure 7, as the frequency of the A string excited is 441 Hz, and the frequency bands are 1/3 octave wide, we can deduce that the balloon plots contain each one a single harmonic of the radiation spectrum of the violin for this excitation.

We can notice that the shift between the 0° and the 357° intensity measurement is very small which means that the setup is almost stable during a single 28 hours measurement.

Concerning the interpretation of these plots, it's important to specify the orientation of the instrument: the violin is always facing the upper part of the plots as we can see on Figure 6, and the neck of the violin is pointing on Y axis.

Conclusion

From our data it is possible to evaluate all the violin's radiation patterns while bowing for every frequency and plot them in every direction. The machine is only the first step to continue further musical instruments studies, but it might be a good compromise between cost and precision to investigate the string instruments' directivity.

To go further on this study, it would be interesting to compare the results obtained with the bowing machine with the TU Berlin's database [8].

We could also imagine to filter the results by subtracting the noise motor signal from the violin signal after measurement with some data processing, to remove the effect of the motor on the radiation pattern shown in Fig 5.

We could also measure the main bowing parameters: bow force, bow velocity and bow position to the bridge during the experiment to evaluate the excitation stability. Some studies have been already done about setups allowing to measure these parameters without having a big impact on the playing conditions [13]. We could use these kinds of augmented violin in combination with the bowing machine not only to increase and control the stability, but also to study the impact of these parameters on the directivity of the violin.

Something that needs to be improved is the direction change when bowing. Some oscillations are propagating through the bow and metal frame when the linear actuator is changing from upbow to downbow which might disturb the recording of the sound during almost one second around this changing period. We could imagine a short slow down process of the linear actuator just before changing the bowing direction.

The final step of this work would be to model these radiation patterns into spherical harmonics to re-synthesize them in virtual environments. In other words, we could transform all these radiation patterns from intensity isolated points into spherical harmonics functions to recreate the sound of the violin in 3D. It would make them compatible with the existing representations and it would be the first step in the construction of a complex acoustic environment.

Equipped with appropriate sensors and controls to ensure repeatability, the bowing machine could become a reference excitation mechanism for a round robin test in several labs to compare measurement systems for musical instruments' directivity.

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