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Team Teaching for STEAM Education

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First Version of actuation technology of actual physical instruments

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Executive Summary

In this deliverable we present the first version of the actuation technology of real physical instruments.

First we introduce actuated instruments, highlighting Ircam’s COALA smart instrument technology, and the reason why such technology has been developed.

Second we remind some key points of the theory: Fourier transform, partials, harmonicity, transfer function. These notions are important and necessary in order to understand the true aim of the deliverable.

Finally, after describing the prototype that is at the heart of this deliverable: the acoustical identification of a simple music instrument (here a steel plate) to reveal its acoustical and musical properties. We provide with results and we discuss how we could develop the prototype further in the scope of iMuSciCA.

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04-09-2017	0.1	Robert Piechaud (IRCAM)	Initial content
16-10-2017	0.2	Robert Piechaud (IRCAM)	Finalised and sent to quality assurors.
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Disclaimer

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LIST OF ABBREVIATIONS

Abbreviation	Description
ATHENA	ATHENA RESEARCH AND INNOVATION CENTER IN INFORMATION COMMUNICATION & KNOWLEDGE TECHNOLOGIES
UCLL	UC LIMBURG
EA	ELLINOGERMANIKI AGOGI SCHOLI PANAGEA SAVVA AE
IRCAM	INSTITUT DE RECHERCHE ET DE COORDINATION ACOUSTIQUE MUSIQUE
LEOPOLY	3D FOR ALL SZAMITASTECHNIKAI FEJLESZTO KFT
CABRI	Cabrilog SAS
WIRIS	MATHS FOR MORE SL
UNIFRI	UNIVERSITE DE FRIBOURG
3D	Three dimension(al)

1. Introduction to actuated instruments

1.3. Why does a music instrument sound "good"?

What makes the difference between a "good" and "bad" guitar? The question is naive, yet legitimate, and the answers are complex and far from being resolved as of today.
And one could also think that, using some technology, a "bad" instrument could be turned into a "good" one, without "carving the wood".
However, the reality is a bit more complex, and the main focus of this prototype is mainly to understand and measure certain simple vibrating structures, which inner acoustical or musical properties can be revealed with the technology we propose.
In fact, once the structure is *actuated* - that is, equipped with sensor and actuator (see below) - the analysis, using various tools, displays its harmonic or non harmonic properties (as we define these notions later in the document). And the analysis stage is also the first step in a strategy where changing the sound of an acoustical structure in real time can be sought.
With this in mind, comparing the analysis and the perception can be an illuminating experience for the student.

1.2. What are actuated musical instruments?

Unlike many other activities and technologies of iMuSciCA's workbench, the actuation technology happens in the "real world". Below is a definition of an actuated instrument and a description of its components.

1.2.1 Actuators

Actuator[1] is another word for "motor". For actuated musical instrument, an actuator is generally the motor of a loudspeaker, that is, a loudspeaker without its membrane. Equipped with an actuator, a music instrument becomes its own loudspeaker.

Fig.1: The Daytonaudio DAEX25 mini actuator.

[1] https://en.wikipedia.org/wiki/Actuator

1.2.2 Sensors

A *sensor*[2] is a device that is able to capture a phenomenon and turn it into an electric signal. For actuated musical instrument, we use piezoelectric sensors to capture the vibration punctually on some resonating part.

1.2.3 Real time processes

By real time, we mean a system that, fast enough, is able to process the incoming signal and to output the result sample by sample (bufferless), in a timely deterministic fashion. A real time process aims at being as close as possible to the physical phenomenon.

1.2.4 Actuated music instruments in short

An actuated instrument is generally made of:

- A real instrument: a guitar, a violin, an idiophone etc.
- One or multiple pairs of actuators and sensors located at the resonating body
- A real-time system - analog or digital - being able to listen to the signal (sensor), to process it, and to reinject the resulting signal through the actuator ; this is why we say that the instrument is *actuated*.

The main idea behind an actuated musical instrument is to provide with tools to identify and analyse its physical (acoustical) properties, and possibly to modify its acoustical behavior (or its playability) using actuators and sensors in real time.

NB: Actuated music instruments works the same way as actively-controlled structures used in earthquake engineering for instance… but with very different goals!

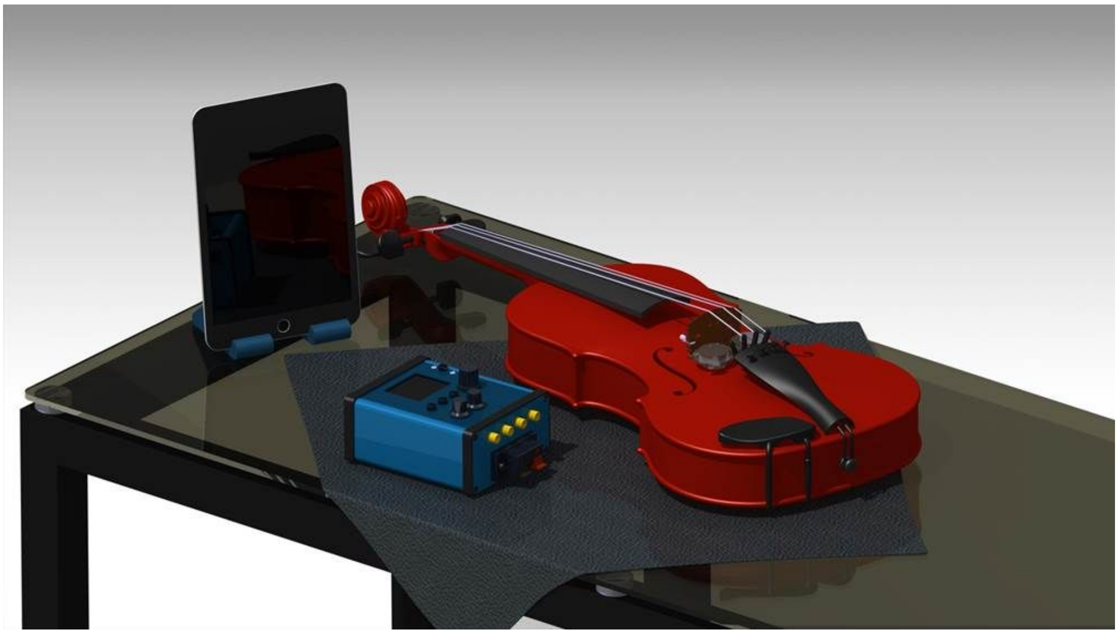

Fig.2: The Coala v2 device and its environment: a typical setup (3D view).

[2] https://en.wikipedia.org/wiki/Piezoelectric_sensor

2. Installation and technical requirements

The current setup is made of:

- a Coala v2 device
- a computer/tablet/phone connected to the Coala over Wifi using any browser (no special requirement)
- a free resonating rectangular steel plate equipped with a pair of sensor/actuator, connected to the Coala.

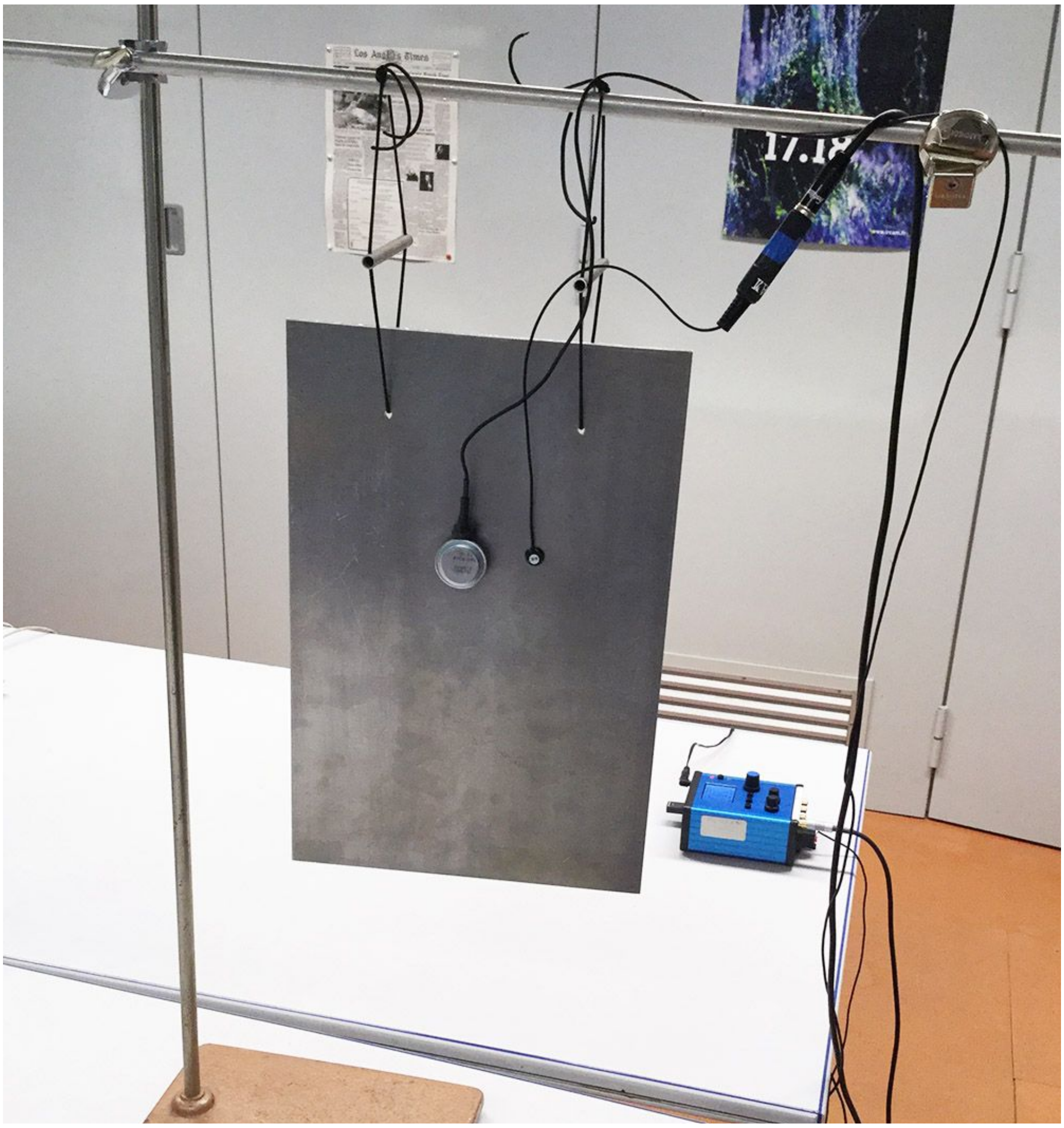

Fig.3: The prototype setup: a steel plate equipped with sensor & actuator connected to the Coala v2.

Once the plate, sensor and actuators have been set up and plugged in, the Coala must be turned on. After a few seconds, the software will automatically run and the Wifi will be enabled, with the embedded web server.

3. Description of the demonstrator

3.1. The Coala v2: a real time active control system

Coala, initially as a part of the IMAREV[3] project, is a device family that has been developed by Ircam since 2014. Its main purpose is to perform active control of sound and structures in an embedded environment. The software side of the Coala is called Active Control Framework[4].

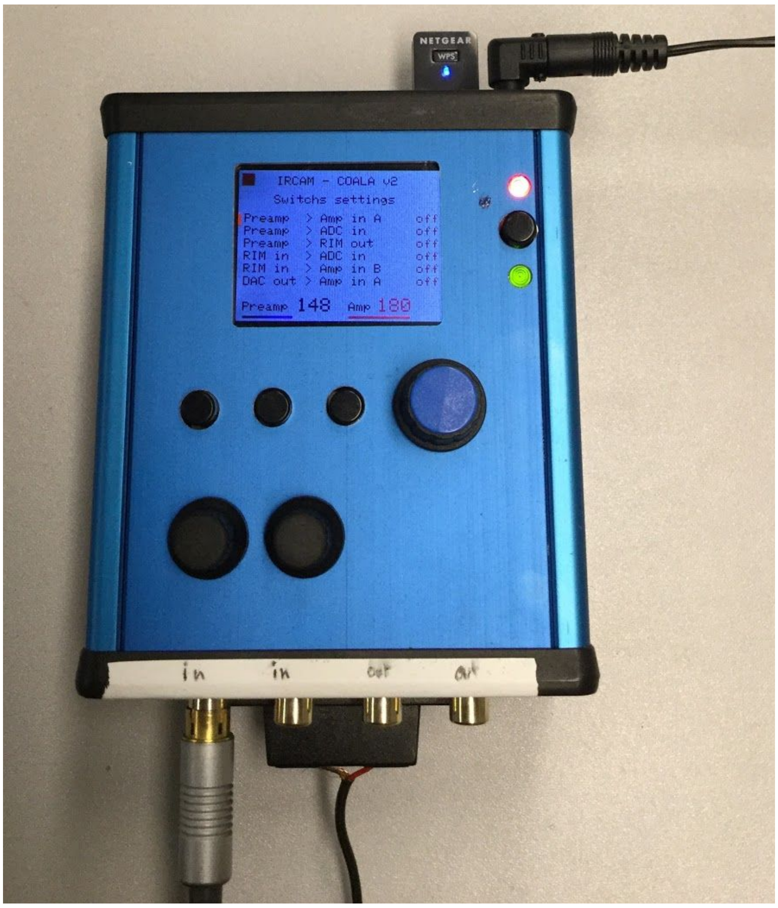

Fig.4: The Coala V2

The Coala v2 features:

- Embedded ARM-based computer Beaglebone Black[5]
- Debian+Xenomai 2.7 Real Time OS
- built-in WIFI hotspot
- Custom cape with:
    - Ultra low latency ADC-DAC
    - Power amplifier (15W)

[3] http://instrum.ircam.fr/imarev/
[4] http://instrum.ircam.fr/real-time-linux-workshop-2014/
[5] https://beagleboard.org/black

- SISO (Simple Input, Simple Output)
- Line Input
- LCD color screen
- Digital potentiometers and switch
- Active Control Framework v. 2.1
- Wifi hotspot with built-in Web- and OSC servers.

Fig.5: The Coala v2: screen controls and Wifi dongle

3.2. The instrument

The simplified music instrument we use in this prototype is an idiophone: a free resonating rectangular steel plate, of dimension (250x380x3mm), equipped with a pair of sensor/actuator, connected to the Coala. We can find some similar types of bell plates (without the sensor/actuator, though) in contemporary music.

The sensor and the actuator have been placed near the center of the plate, but not right in the center, in order to avoid "dead" parts, that is, points of the resonating body which are almost not resonant (also known as node points[6]). The determination of a good location for actuators and sensors is generally empirical.

3.2.1 Static influence of the actuator and sensor on the resonating body

It is a known fact the an actuator or a sensor, or both, can be significantly intrusive when added to a resonating body. In other word, the addition of the such devices, even of small size, can influence

[6] https://en.wikipedia.org/wiki/Node_(physics)

the natural sound of the instrument, especially with regards with the decay. However, it is beyond the scope of iMuSciCA to study or measure this influence.

Fig.6: The steel plate equipped with a sensor (piezo) and an actuator.

Here we can hear the sound of the plate, after having been equipped with sensor and actuator, hit with an orchestral soft mallet:
http://www.imuscica.eu/wp-content/uploads/2016/11/metalplate.wav

3.3. Starting up the Coala

3.3.1. Connecting to the Coala over Wifi

Using a tablet, a smartphone or a computer, the connection over Wifi can be established at the hotspot “CoalaV2”. In a browser, the following fixed IP will connect to Coala’s built-in webserver:

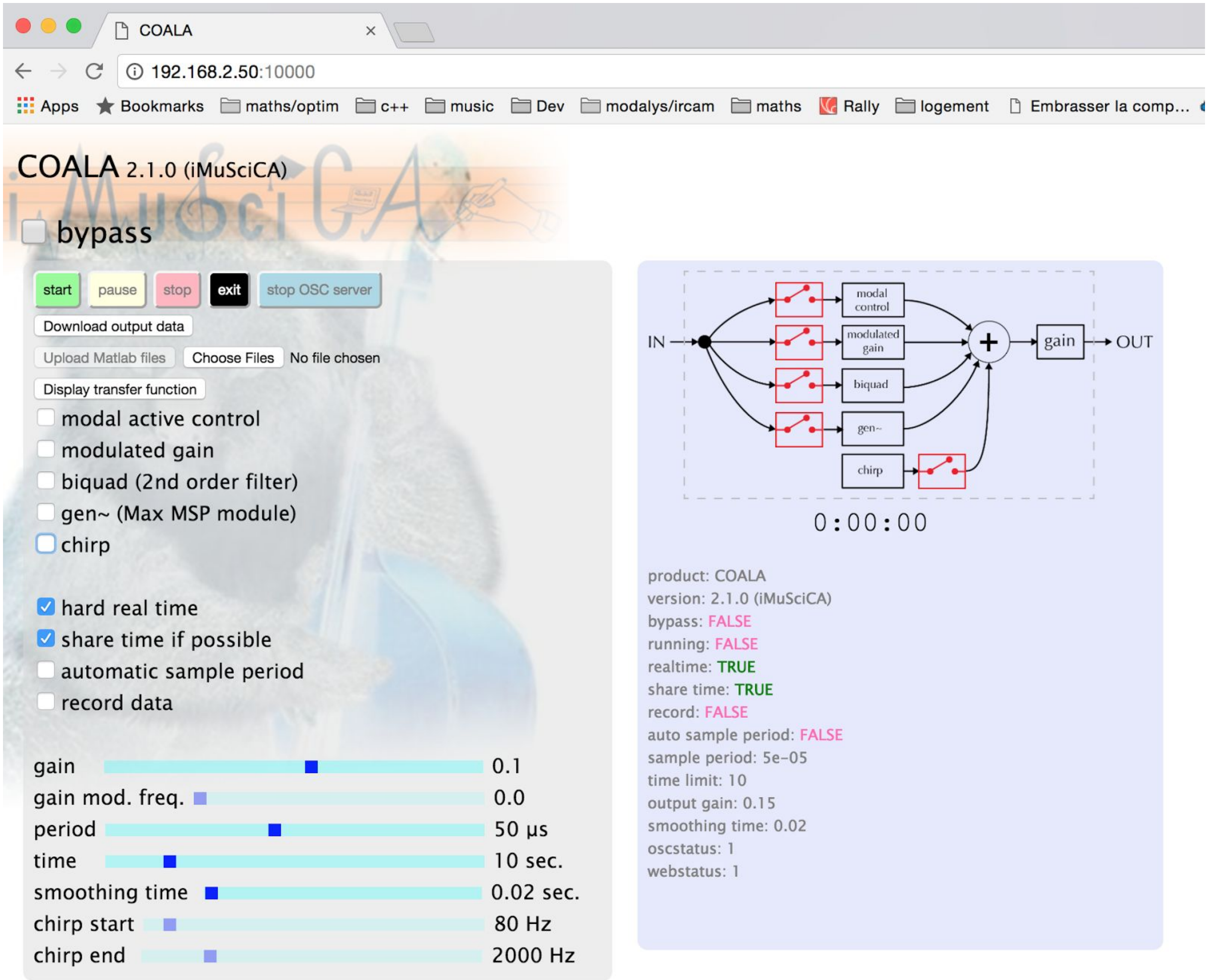

Fig. 7: The Coala web interface.

The Coala web interface has two parts - leftward and rightward - representing the user controls and the state, respectively.

3.3.2. User controls

Currently, in the user controls, we find:

- A player: start/pause/stop/exit/stop osc server.
- Some specialized functions: download output data, upload matlab files, display transfer function.
- Some checkboxes enabling certain modules: modal active controls, modulated gain, biquad, gen~ filter, chirp.
- Some general checkboxes: hard real time, share time, automatic sample period, record data.
- Some sliders corresponding to various parameters: input gain, modulated gain frequency, period (sample time), smoothing time, chirp start/end.

Finally, a larger checkbox “bypass” is available above the left control panel.

NB: in a later version of the Actuation Technology, we will present a simplified interface, since not all functions are used within the scope of iMuSciCA.

3.3.3. Device state

The state panel provides with:

- schematics of the current state of Coala: each module and its state is represented in relation with the input and output,
- a text block giving key information.

3.4. The experience: identifying the resonating structure

3.4.1 Fourier transform, partials, harmonicity

To say it short, the Fourier transform[7] (or representation) of a signal, i.e. a time/amplitude function - here a sound, is a mathematical operation which results in a unique frequency/amplitude function. Restricted in practice to a relatively short time span, it allows to "see" a sound as a unique sum of simple frequencies, that is, as a unique linear combination of sines and cosines. This sum is infinite in theory, but in practice, we restrict it to a finite number of frequencies.

3.4.1.1 Partials

The *partials* of a sound (at time t) are the frequencies expressed in its Fourier transform around time t.

3.4.1.2 Fundamental frequency

The *fundamental frequency* of a sound is the smallest frequency found in its Fourier representation. We sometimes write this frequency f_0.

3.4.1.3 Harmonicity

We say that a sound is *harmonic* when each frequency found in its Fourier representation is a whole multiple of its fundamental frequency. We say that a sound is inharmonic when that is not the case.
NB: musical sounds (ex: a guitar string, a flute sound) tend to be harmonic, while what we call "noise" tend to be inharmonic.

3.4.2. Transfer function

The transfer function of the structure can be described as its acoustical signature, or, more explicitly, as the way the structure filters any small perturbation applied to it.
The transfer function is not just a mathematical object, it strongly corresponds to our perception. Here are a couple of examples:

1) When you speak in a tube, your voice is filtered and altered by the characteristic modes of vibration of the tube.
2) When a guitar string is plucked, the string vibration is first transmitted via the bridge to the soundboard, and to the ears via the air (radiation).

These phenomena can be entirely described by transfer functions.

[7] https://en.wikipedia.org/wiki/Fourier_transform

In our case, the process for getting the transfer function consists in sweeping[8] a broad frequency range, recording the result, and finally comparing the input and the output in the frequency domain (Fourier).

3.4.3 The identification

The identification process of the structure - here the resonating plate - can be described as follows:

- A chirp (i.e. a sweep) is sent to the structure via the actuator (the input X).
- The sensor records the signal (the output Y).
- The transfer function, i.e. the Fourier transform of the ratio Y/X, is represented.

3.4.4. Sending the sweep sound

We chose a range of 100 to 1400 hz for our chirp, and we can hear the result as filtered by our metal plate: http://www.imuscica.eu/wp-content/uploads/2016/11/chirp.wav

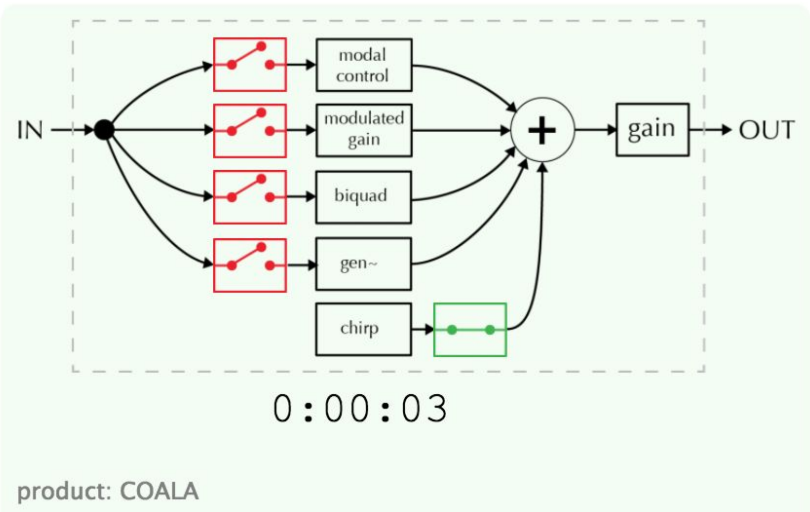

Fig. 8: Coala schematics state while sending the chirp.

3.4.5. Displaying the transfer function

Once the chirp is over, the user will click on the "display transfer function" button to get the result. As stated earlier, the transfer function is the Fourier transform of the output over the system input. So in abscissa are the frequencies (ranging from 100 to 1400 Hz) and in ordinate the amplitude (in DB):

[8] The are other methods such as pseudo-random noise.

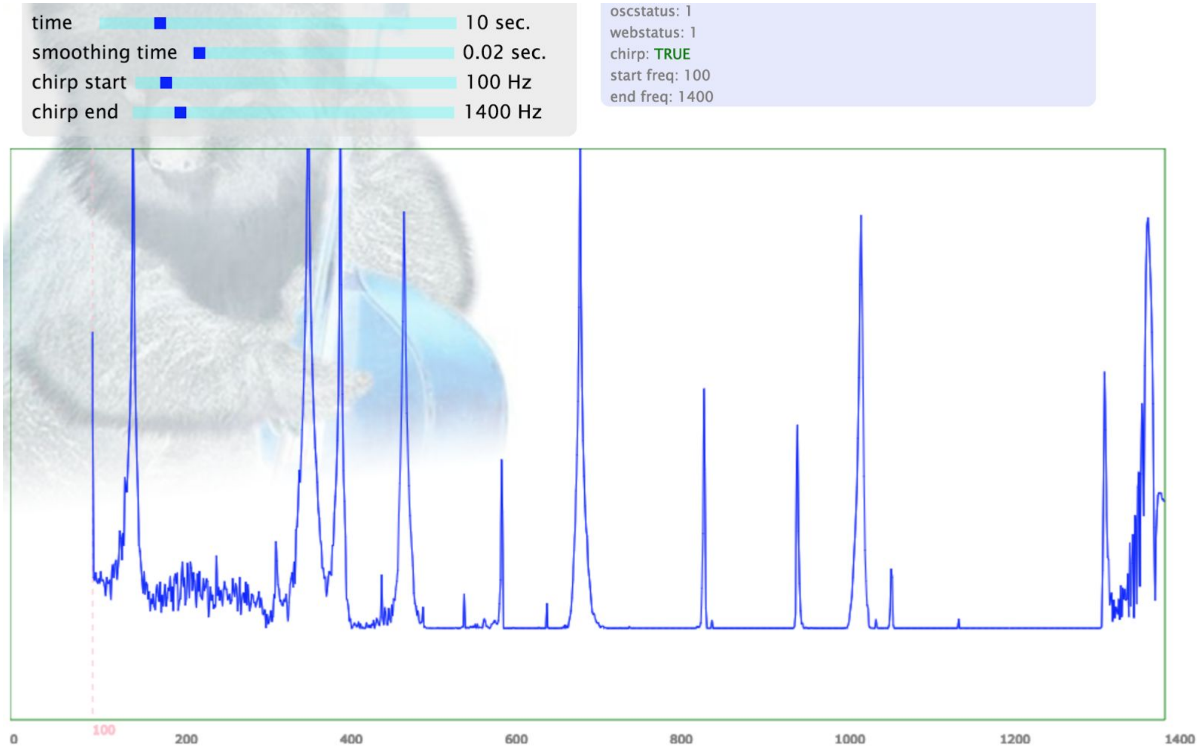

Fig. 9: The transfer function result, after sending a chirp to the structure. Here, x-axis corresponds to frequencies (ranging from 100 to 1400 Hz), whereas y-axis corresponds to amplitude in dB.

The peaks of the functions represents the frequencies where the structure gets particularly excited.

3.4.6. Identifying the mode frequencies

In this first version of the prototype, we now need to manually infer the corresponding frequencies by chasing the peaks, using, for example, this note-to-frequency table: https://pages.mtu.edu/~suits/notefreqs.html

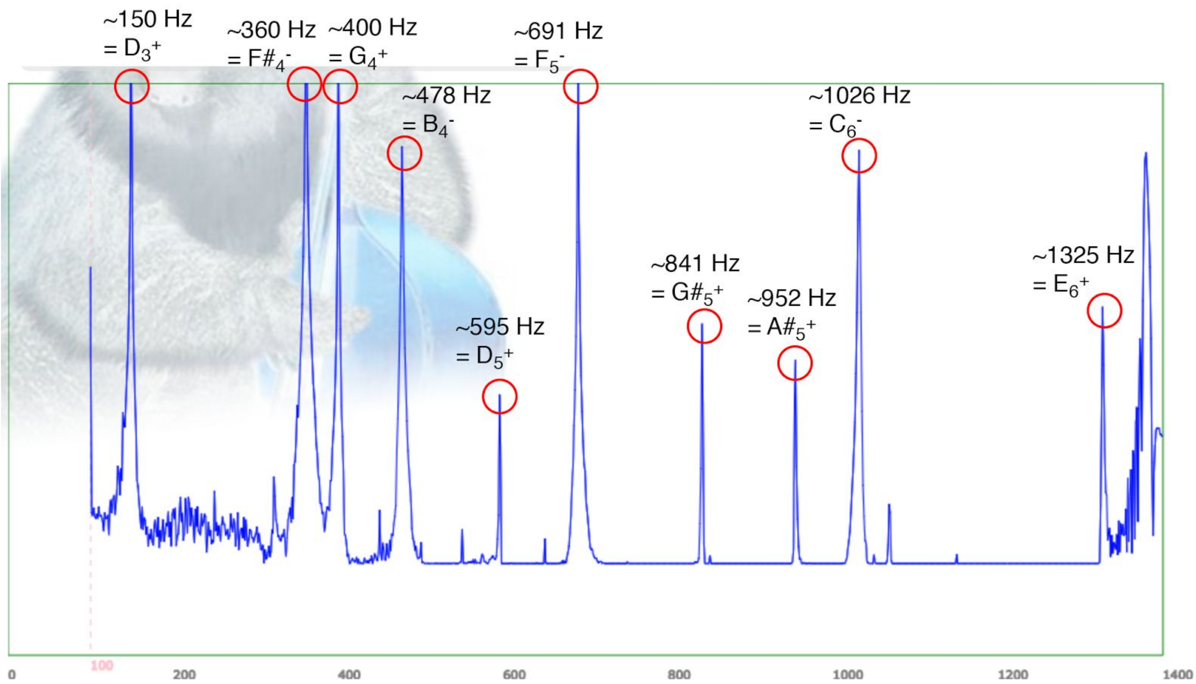

Fig. 10: The transfer function with identified peaks and approximate corresponding musical notes.

NB: it is a good idea to ignore the neighbourhood of the extreme sides of the range (around 100 Hz and 1400 Hz) given that they generally tend to be "noisy".

3.4.6.1 Eigenfrequencies

The peak frequencies of the structure are also called *eigenfrequencies*.

3.4.7. Displaying the eigenfrequencies as notes

Finally, using the music notation software Finale[9], we can represent the corresponding eigenfrequencies as a note sequence. For students with a musical background, this representation is probably more natural than a graph:

Fig. 11: The note sequence of the partial frequencies identified on the resonating structure.

NB: The plus/minus signs by the note accidentals suggest that the notes are not "tempered", i.e. they generally do not correspond to "perfectly" tuned[10] notes.

[9] https://en.wikipedia.org/wiki/Finale_(software)
[10] According to the Western equal temperament. See https://en.wikipedia.org/wiki/Equal_temperament

This score representation highlights the fact that the series of partials (as defined earlier) is far from being harmonic, which matches the perception we have of a rather complex sound when hitting the plate with a mallet.

3.4.8. Comparing the transfer function and the sound

It is interesting to compare the result found above and the sound of the plate itself when hit by a soft mallet about the center, and displayed using the Snail:

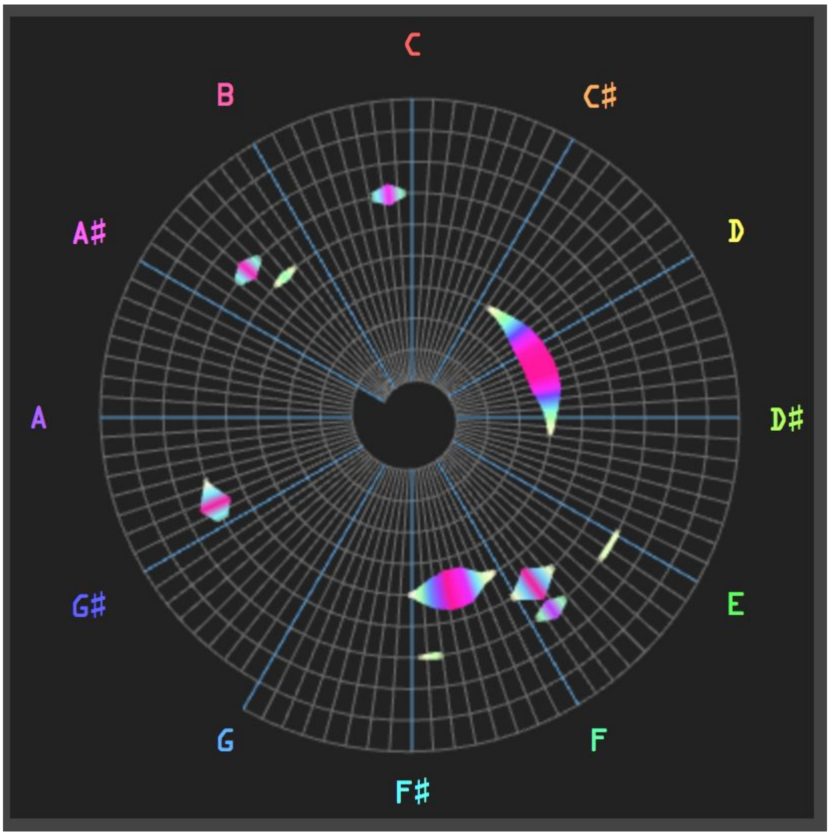

Fig. 12: The sound of the plate when hit with a mallet, analysed with the Snail.

The Snail representation in Fig.12 highlights some particular "notes" (that is, partials) while hitting the plate with a mallet: D3 (the lowest), F4#-, F5 etc. Comparing these and the eigenfrequencies we found through the analysis above (see Fig. 10 and 11), we can see that, although some are common, there are differences. This is partly due to the fact that the sound richness (in term of partials) when hitting depends greatly on the impact point[11]. Finally, the analysis tends to provide with a richer "cartography" of the resonating structure.

NB: Keep in mind, that the transfer function is not a sound by itself, it is the *inner signature* of the resonating structure, in which, in fact, a particular sound will result when playing the instrument.

[11] A phenomenon that the iMuSciCA Modalys examples also demonstrate. A good percussionist knows exactly where to hit an instrument to make it sound "good".

3.5 Future iterations of the prototype

In a near future, we aim to implement the following within the web interface:

- Automatic identification of the eigenfrequencies (possibly with amplitudes)
- Built-in score (music notes) representation

Also, as previously stated, the Coala interface will be simplified in order to be clearly understood by students.