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## Ultrasonic components of musical instruments

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There are few works characterizing the ultrasonic components emitted by musical instruments, primarily because it did not seem worthwhile to measure an energy that was difficult to register and that it is not perceived by humans. Registering sounds over 20 kHz is possible today with typical audio equipment. There exists low-cost equipment such as microphones, sound cards and speakers that work with frequencies extending the traditional HiFi standard. The possibility of perceiving frequency components over the audible range is still a matter of debate, but we think that it is important to know how much energy there is in musical instruments in the ultrasonic range in order to fuel that debate. In a previous work, our research group performed energy measurements over the standard audible range for some musical instruments. This paper reports new findings about the ratio of high to low frequency energy over time for several musical instruments and different angles.



## 1. INTRODUCTION

The audibility range extends from 20 Hz up to around 20 kHz, although its sensibility decays under 100 Hz and above 10 kHz. Most of speech sound energy is located within this range (100 Hz – 10 kHz). Musical sounds have evolved to stimulate audition in its full range, but between 100 Hz and 3 kHz is where the information of greatest interest is located<sup>1</sup>.

The frequency response analysis of musical instruments usually focuses on characteristics such as impedance and admittance variations across frequency. Some studies are based on mathematical models related to the frequency response function while others concentrate in the experimental measures of certain instruments. Most of these studies analyze frequencies between 100 Hz and 3 kHz, although some of them extend their analysis to the whole audible range.

There are very few studies about the sound energy of musical instruments above 20 kHz. At first sight it could be reasonable because energy above 20 kHz might not be perceived by people.

The possibility of perceiving a sound stimulus above 20 kHz is still subject of debate. There are reports suggesting that it is possible to perceive pure tones at 25 kHz and above, in certain conditions, as stated by Ashihara<sup>2 3</sup> and Canalis<sup>4</sup>. Oohashi<sup>5</sup> and Nishiguchi<sup>6</sup> sustain that perception of higher components is possible only when they are emitted at the same time as audible audio components. This debate gets more relevant in the attempt to determine the technical characteristics required to register audio with conservation purposes, keeping in mind those current high resolution audio formats that enable the recording of high-frequency components rather than traditional formats.

According to the Nyquist Theorem, the sampling rate must be at least twice the highest analog frequency component of the signal (not the highest perceived frequency). If the components of the original signal run over the Nyquist frequency it is necessary to limit them by means of an antialiasing filter, altering the phase components of the signal at least a decade around the cutoff frequency of the filter. If the ultrasonic energy of musical instruments was significant, the use of antialiasing filters with a cutoff frequency under the Nyquist frequency would result in some kind of misrepresented audible components of the original signal.

The characterization of acoustic energy emission above the audible range can provide useful information to the debate about the relevance of making registers that preserve the high-frequency components in musical recordings.

## 2. SOUND ENERGY BEYOND AUDIBLE RANGE

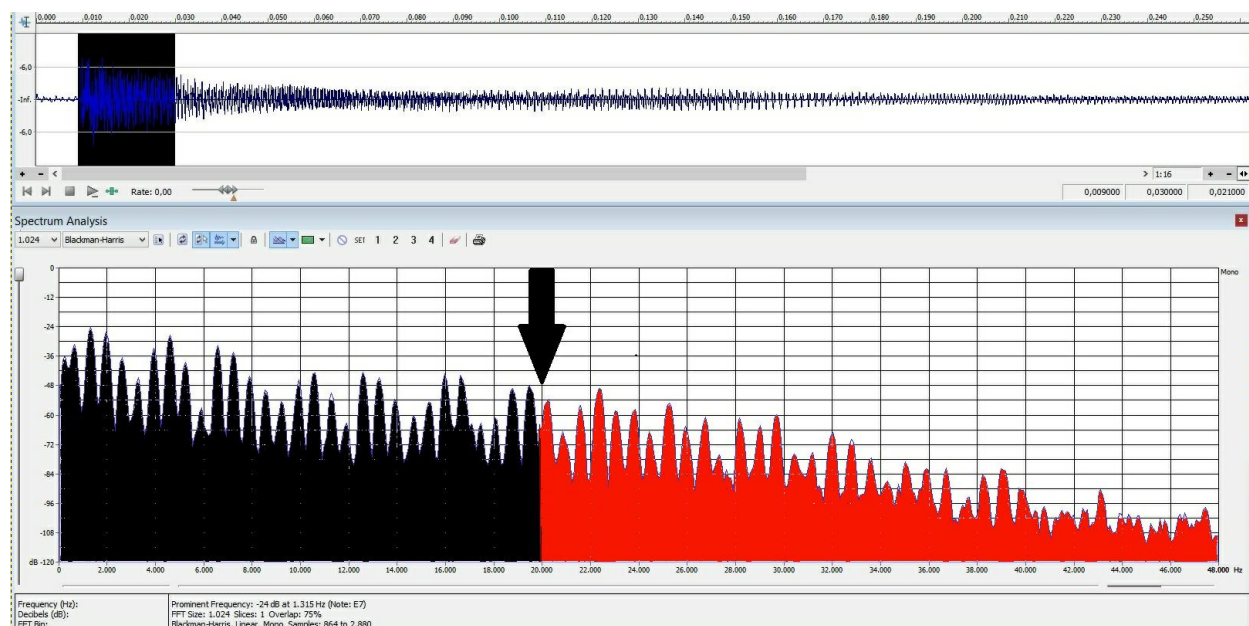
Oohashi has made several studies in relation with the possibility of perceiving frequency components above 20 kHz in gamelan music. He reported brain activity and perceptual differences in subjects that were listening to different gamelan music fragments, comparing versions where the only difference was sound components above 22 kHz<sup>7 8</sup>. Even though his work stated that gamelan music instruments are rich in very high frequencies components between 20 kHz and 50 kHz there is no precise information published about these characteristics. The power spectrum of gamelan instruments included in his initial papers was run over an analysis period of 200 s. In another paper, Oohashi<sup>9</sup> recorded and studied the spectrum of some musical instruments with an analysis period of 1.2 s. The main aim of Oohashi's work was to determine perception, not to measure the instruments spectrum. The different time window considered in these studies made the results somehow difficult to compare with other instruments or other experiments. If a musical instrument produces high frequency components in a short

period of time (e.g., the attack of one note), the report of a power spectrum that runs over a long period of time does not represent accurately those high frequency components.

Oohashi states that even when subjects were not capable of perceiving pure tones beyond the audible spectrum, the presence of ultrasonic components that complement sounds within the audible range generated differences in the subjects' brain activity.

One of the few reference works about energy above 20 kHz measurements in musical instruments has been widespread by James Boyk of CalTech<sup>10</sup>. The fact that this unpublished work is mentioned in several recent publications<sup>11 12 13</sup> reinforces the assumption that there is a lack of systematic studies in this area. Boyk's work captures spectrum samples in certain moments of the recording with an analysis window of 21 milliseconds, without analyzing the variation of these components throughout time. He reports significant energy levels for various types of musical instruments.

Our team recently submitted some preliminary spectral measurement results that show a very interesting level in high-frequency components in musical instrument acoustic emissions<sup>14</sup>. The spectrum of a note emitted by a string-pulsed instrument at the time of the attack is showed in Fig. 1. The register corresponds to a charango, a native instrument from the Cordillera de Los Andes region.



*Figure 1. Charango's spectrum. The components colored in red exceed the audible range.*

### 3. METHODOLOGY

#### A. ENERGY LEVEL CHARACTERIZATION

In previous studies we obtained the spectrum of some musical instruments, for example, at the attack of a string-pulsed instrument. A filtered copy (containing only the components outside the audible range) of each high resolution sample was made. The energy level was obtained by comparing all the energy contained in high frequencies in relation with the total amount of energy.

In this work we decided to modify the frequency zones that should be compared. In our recordings the components barely exceed the 40 kHz, so the high-frequency zone is confined to an octave (20 kHz to 40 kHz).

We considered that a clear way to express the variation of the high frequency energy levels was to compare the amount of energy in the high-frequency octave band with some other octave band that could characterize, at least partially, the instrument sound emission. We decided to do the energy measurements in three octave bands. The central frequencies of the selected octaves are 2 kHz, 16 kHz and 32 kHz in accordance with the ANSI S1.11-2004 standard.

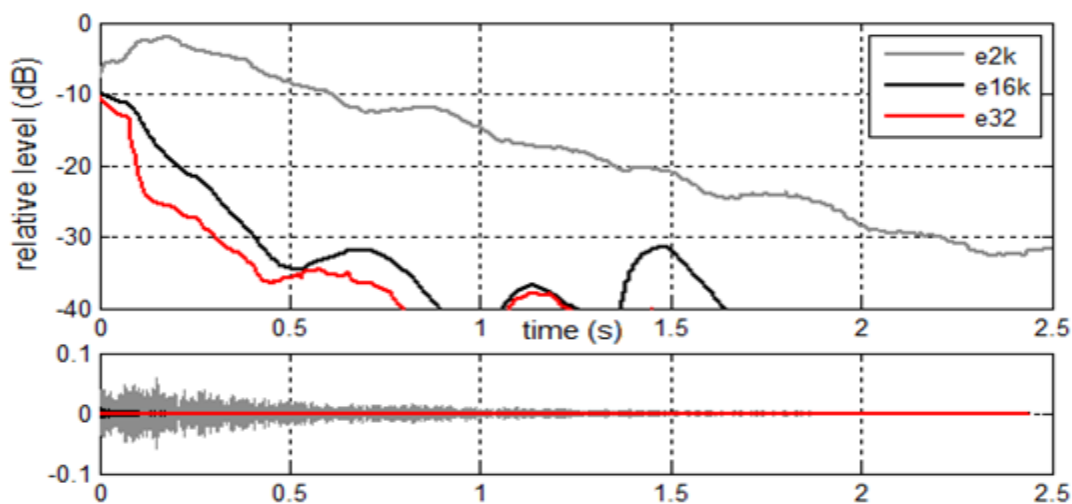
In terms of these energy bands we will suggest the use of two indicators to characterize the high frequency energy of musical instruments. The first arises from comparing the energy level of the 32 kHz band (above the audible range) with the energy level of the 16 kHz band (higher band within the audible spectrum). The second indicator stems from comparing the 32 kHz band energy level with the 2 kHz band which combines high sensitivity of the human ear with significant energy level of sound samples.

The recordings were made with an Earthworks M30 measurement microphone and a Native Instruments Komplete Audio 6 interface working at 96 kHz, 24 bits. The microphone's frequency response is almost flat up to 30 kHz, with a slight 3 dB drop around 40 kHz. This drop in the frequency response was not compensated in the results presented below.

The recordings were processed with MATLAB to obtain filtered samples per octave bands. The temporal energy variation in the 32 kHz band is calculated in Eq. (1), where  $p_{32k}(t)$  represents the audio data processed with an octave band filter with a central frequency of 32 kHz, and  $e_{32k}$  represents the energy of that octave band obtained with a temporal integration window  $T$ .

$$e_{32k}(t) = 10 \cdot \log \left( \int_t^{T+t} p_{32k}(\tau)^2 d\tau \right) \quad (1)$$

The temporal integration window used has a period  $T=125$  ms following the 'F' integration time of IEC 61672-1 standard. Through a similar procedure  $e_{16k}(t)$  and  $e_{2k}(t)$  were obtained, with octave filters centered in 16 kHz and 2 kHz respectively. The temporal behavior of these variables is shown in Fig. 2. It can be seen that all three energy levels are comparable in attack.



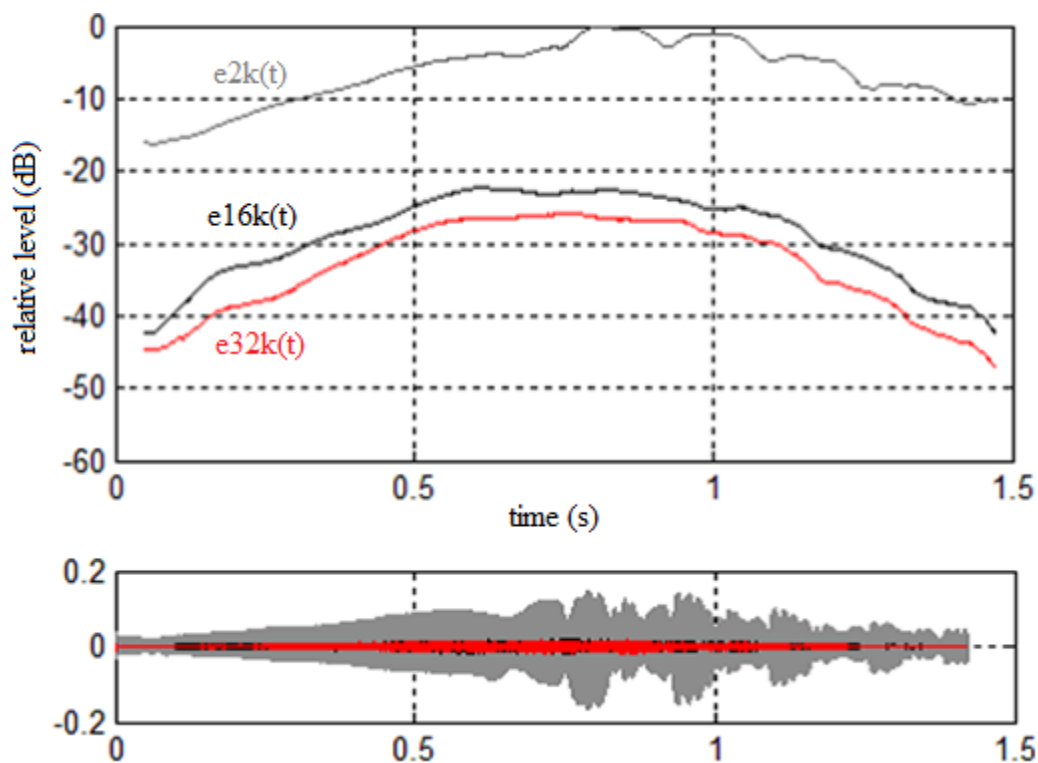
**Figure 2. Energy per octave time graph of a cymbal.**

## B. RESULTS

Preliminary results are obtained in three topics:

- Short-time energy diagrams are obtained for different musical instruments.
- Octave energy ratios vs. time graphs comparing the ultrasonic components with octave bands in the audible range are presented.
- Maximum and minimum ratios are summarized in Table 1.

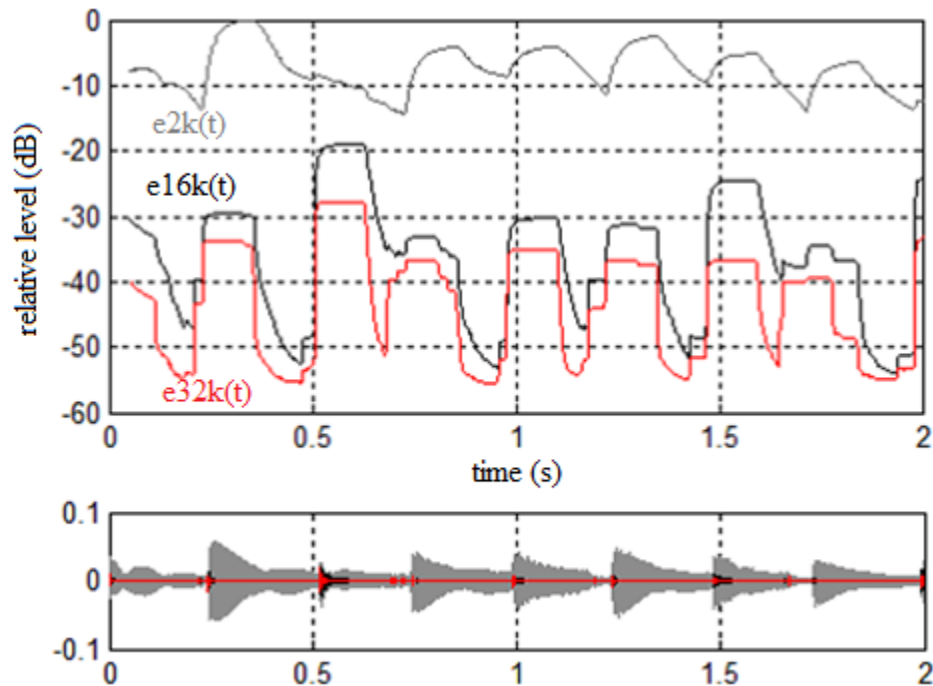
The short-time energy diagram per octave bands of a violin note is shown in Fig. 3, superimposing the time domain plots as a reference. Gray traces represent variations of energy in the 2 kHz octave band, black trace corresponds to 16 kHz band, and red trace is related with energy in the ultrasonic range.



*Figure 3. Energy per octave time graph of a violin.*

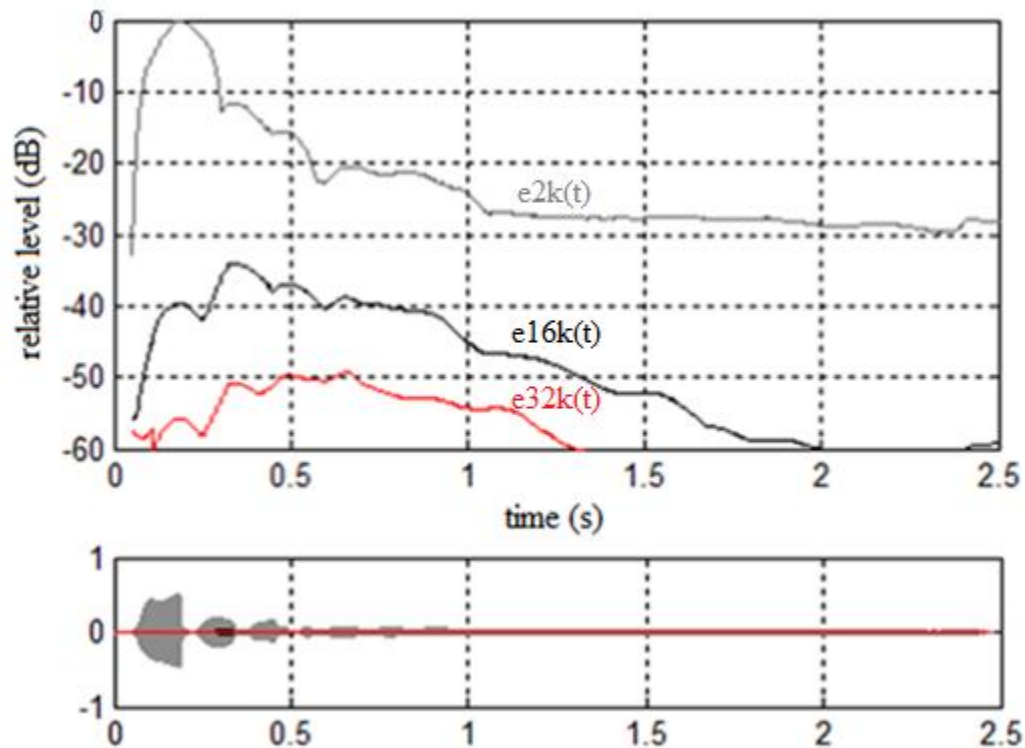


The time variation of Energy per octave band of a charango is shown in Fig. 3.



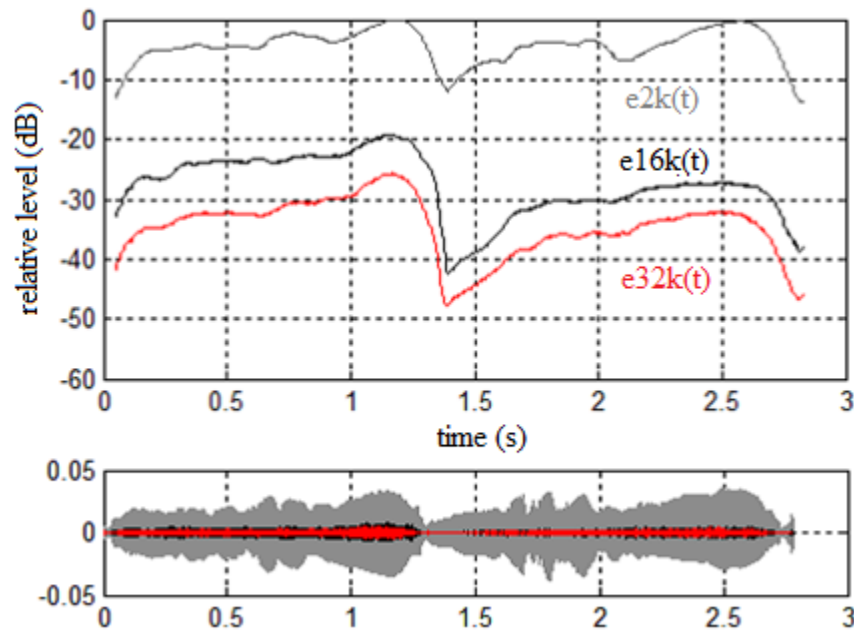
*Figure 3. Energy per octave time graph of a charango.*

The bandoneon is a type of concertina particularly popular in Argentina. It is an essential instrument in most tango ensembles. Its energy vs. time graph by band is represented in Fig. 4.

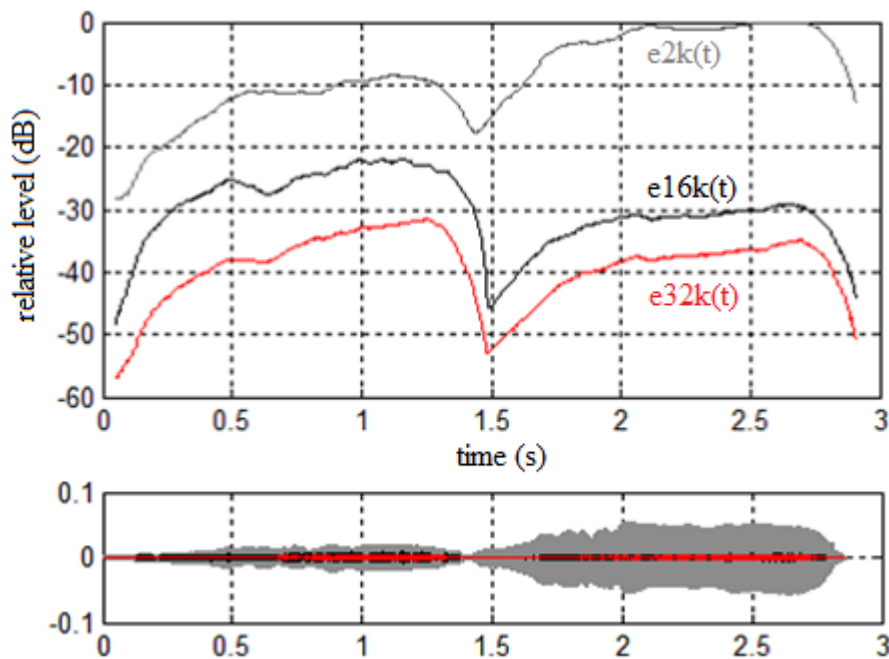


*Figure 4. Energy per octave time graph of a bandoneon.*

In order to consider the effect of directivity in the energy patterns of the different octave bands, the energy variations of the same cello fragment were captured from different angles. Fig. 5 shows the results of recording sound with a microphone 10 cm away from the bridge in a perpendicular angle to the strings. In Fig. 6 the microphone is kept at 10 cm from the bridge but with a 45 degrees angle to the strings. In Fig. 7 the microphone's distance remains the same, but at 90 degrees from the original microphone position, placing it in a parallel position to the strings plane.



*Figure 5. Energy per octave time graph of a cello (at 0°).*



*Figure 6. Energy per octave time graph of a cello (at 45°).*



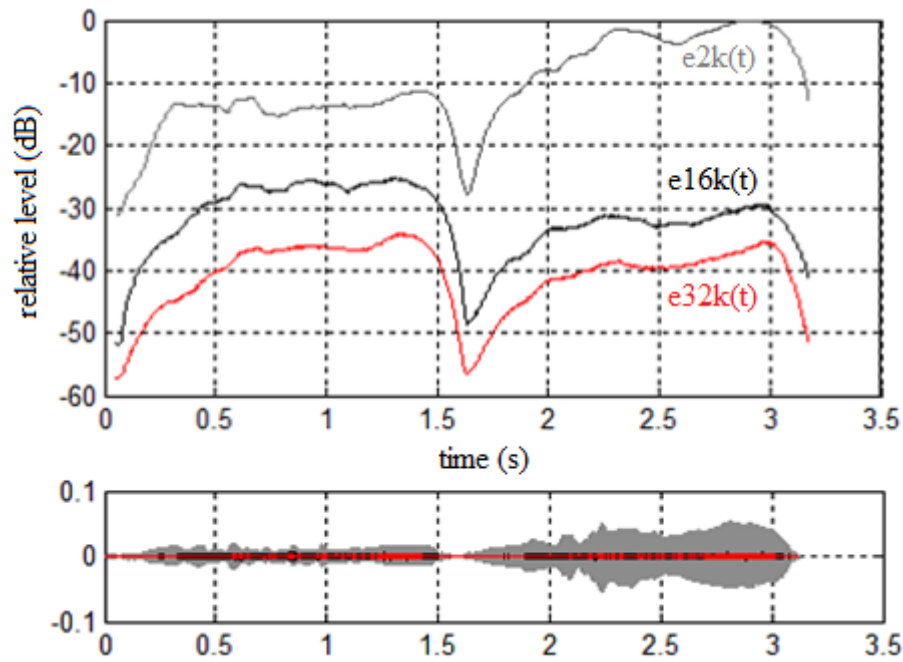


Figure 7. Energy per octave time graph of a cello (at 90°).

According to these results of energy band over time, we suggest two indexes by simply subtracting the different short-time energy curves, as stated in Eq. 2.

$$\begin{aligned} hf16(t) &= e32k(t) - e16k(t) \\ hf2(t) &= e32k(t) - e2k(t) \end{aligned} \quad (2)$$

An index of  $hf16 = -12$  dB means that the contained energy in the 32 kHz octave band is 12 dB lower than the energy of the 16 kHz band. It is important to establish that these indexes values are useful only when sound levels are significantly above ambient noise. In moments of silence or very low sound levels, the indicators will give inaccurate results, comparing the energy levels of the ambient noise. Fig. 8 shows both index vs. time graphs applied to the record of a cymbal.

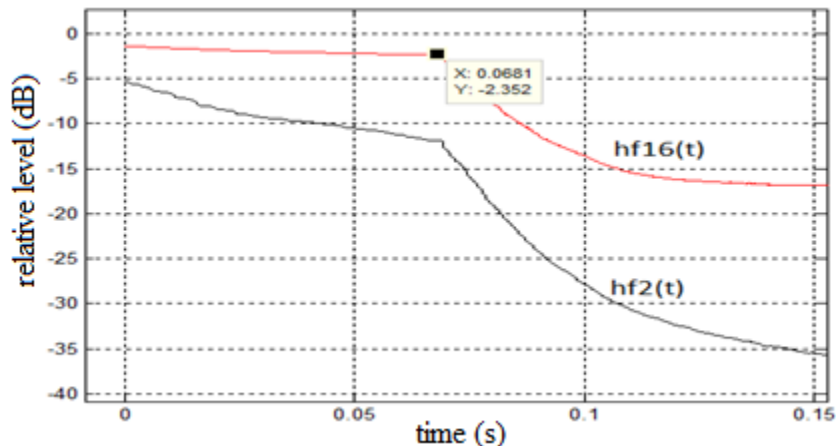


Figure 8. Octave band energy ratio over time for a cymbal.

Using the proposed indexes it is possible to obtain minimum and maximum values to compare musical instrument variations in high frequency energy in a compact manner. Table 1 sums up maximum and minimum results of the analyzed instruments.

*Table 1. Maximum and minimum energy ratios.*

Musical Instrument	hf2 max	hf2 min	hf16 max	hf16 min
<b>Cymbal</b>	-5 dB	-36 dB	-1.5 dB	-16 dB
<b>Violin</b>	-24 dB	-32 dB	-3.5 dB	-4.5 dB
<b>Charango</b>	-15 dB	-18 dB	-2 dB	-8 dB
<b>Bandoneón</b>	-30 dB	-55 dB	-8 dB	-15 dB
<b>Sax</b>	-48 dB	-50 dB	-6 dB	-10 dB
<b>Cello 0°</b>	-26 dB	-36 dB	-6 dB	-9 dB
<b>Cello 45°</b>	-22 dB	-38 dB	-5 dB	-13 dB
<b>Cello 90°</b>	-28 dB	-37 dB	-5 dB	-12 dB

## 4. CONCLUSION

Ashihara reports the possibility of perceiving pure tones above 20 kHz, at least when high level signals were used (108 dB<sub>SPL</sub>). The energy generated by musical instruments in this frequency range is expected to be far below this value. Normally this consideration seems enough to rule out any interest in high frequency components because it is assumed that even if it exists, it surely would be of a low level. But when a short period of time is considered we have shown that a cymbal, for example, generates high frequency energy only 5 dB below the energy of the 2 kHz octave band.

On the other hand, from a technical perspective, the existence of high level energy frequency components near or above the Nyquist frequency challenged the design of antialiasing filters, if it is intended to preserve all the audible information.

One of the proposed indicators allows to compare the energy of the first octave band out of audible range with the last octave within it. In some instruments (percussion or string pulsed instruments) both band energies are very similar at the attack. In some bowed string instruments the level is also comparable (there are minor differences of 6 dB in violin samples and around 10 dB in cello).

The other indicator allows to obtain a relative energy value respect to the ears maximum sensitivity frequency zone. In the instruments with sharp attack the high frequency energy levels are comparable with the maximum sensitivity levels for some tenths to hundredths of milliseconds.

Our contribution suggests a way to characterize the energy left outside normal audio recordings. It could be useful to take decisions about recording musical sound for future preservation, at least while the subject of the perceptive effects of the frequencies above the audible range is still open.

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