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Evaluación perceptual de diferencias entre sonidos originales y sintetizados de un instrumento musical

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RESUMEN: Para estudiar las propiedades de los instrumentos musicales, comúnmente se utilizan grabaciones en situaciones controladas (sonidos originales) que son comparadas con modelos computacionales (sonidos sintetizados) que recrean dichas situaciones. En este proceso, es habitual la utilización de descriptores objetivos en vez de descriptores perceptuales. El objetivo de este estudio fue utilizar descriptores psicoacústicos a señales grabadas y modeladas de un instrumento musical e identificar si existen diferencias perceptuales. Se eligió un instrumento llamado *Hummer*, el cual genera sonido cuando es rotado a ciertas velocidades, debido a flujos de aire que excitan sus frecuencias de resonancia. Se encontraron diferencias perceptuales en fluctuaciones de sonoridad y rugosidad. Los criterios de evaluación son presentados, así como una discusión acerca de la aplicabilidad de estos métodos en la evaluación de otros instrumentos musicales.

KEYWORDS: Acústica musical, psicoacústica, sonoridad, rugosidad, Frecuencia fundamental.

Perceptual evaluation of differences between original and synthesised musical instrument sounds

ABSTRACT: To better understand the properties of musical instruments, their recordings in controlled situations (original sounds) are often compared with computational models (synthesised sounds) that recreate such situations. When they are compared, objective descriptors are often used rather than perceptual audio (psychoacoustic) descriptors. The purpose of this study was to apply psychoacoustic descriptors to measured and modelled signals of a musical instrument and to identify whether perceptual differences were present in the signals. The hummer was chosen, which is a musical instrument that generates sound when it is rotated at certain speeds, due to airflow exciting the resonance frequencies of the system. Perceptual differences were found for loudness fluctuations and roughness. The evaluation criteria are presented as well as a discussion of the applicability of these methods to the evaluation of other musical instruments.

1 INTRODUCTION

Characterising musical instruments has been always challenging, since each musical instrument has different properties. Some are tonal such as, e.g., the piano or brass instruments, while others are atonal such as some of the percussion instruments. There are also differences in terms of the intensity and which frequency range they cover (higher or lower pitch sounds), to mention just a few aspects. To better understand the properties of instruments, sound recordings in controlled situations are often compared with computational models that recreate such situations. However, when comparing measured and modelled audio signals many researchers make use of descriptors similar to those used in physical applications, electronics or telecommunications where no human perception is necessarily involved.

Even considering that the human hearing system is not yet fully understood, psychoacoustic studies have addressed the problem of sound perception by developing and validating audio descriptors based on perceptual criteria. Psychoacoustic audio descriptors have mostly been developed using artificial stimuli (noise or sine tones) [e.g., 1, 2, 3, 4] and less often using speech, music or other everyday sounds [e.g., 5, 6, 7]. The purpose of this study is to apply perceptual audio descriptors to measured and modelled signals of a musical instrument and to identify whether perceptual differences are present in the signals. The hummer, also known as the “voice of the dragon”, was chosen. For this instrument, a physical model and original sounds measured in different conditions were available [8, 9]. First, an overview of the basic principles of the hummer is given, followed by a description of the psychoacoustic parameters of loudness and roughness and the results of their use in the evaluation. Finally, the evaluation criteria and the applicability of these methods to other musical instruments are discussed.

2 CHARACTERISTICS OF THE HUMMER

The hummer is a flexible plastic corrugated pipe of length L with both ends open. A schematic geometry of the hummer and typical dimensions are shown in Figure 1.

To generate sound, the hummer has to be rotated at a certain speed in order to excite the natural frequencies of the pipe. Higher rotation speeds produce higher pitch sensations. According to fluid dynamics this ‘whistling’ is produced by vortex shedding at corrugations coupled to acoustic

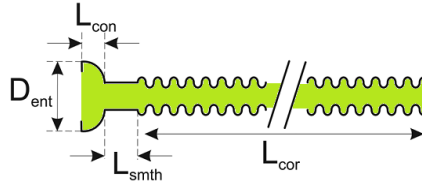


Figure 1: Schematic drawing of a hummer. In this study, $L = L_{con} + L_{smth} + L_{cor} = 70$ cm, the inlet had an entrance diameter D_{ent} of 3.3 cm. The opposite end of the hummer was identified as the outlet.

standing waves. The resonance frequencies f_n of the system as a function of the acoustic mode n are given by Equation 1. Resonance frequencies estimated using Equation 1 and those obtained from measurements (detailed in section 3.1) are presented in Table 1.

$$f_n \approx n \frac{c_{eff}}{2L} \quad \text{with } n = 2, 3, \dots \quad (1)$$

where c_{eff} corresponds to the effective speed of sound in the tube and L corresponds to the length of the pipe. The estimated effective speed of sound is approximately 310 m/s [8].

Table 1: Resonance frequencies for the hummer at different rotation speeds considering both theory (Equation 1) and measurements. Higher acoustic modes represent shorter rotation periods. In this study acoustic modes 2 and 5 were investigated.

Acoustic mode n	Resonance frequency f_n [Hz]		$\Delta F0$ [%]	Rotation period Ω_n [s]	Analysed time [s]
	Theory	Measured			
2	442.9	424.4	4.2	0.6023	2.4092
3	664.3	638.7	3.9	0.3934	-
4	885.7	851.8	3.8	0.2961	-
5	1107.1	1061.7	4.1	0.2688	1.0752

The rotational movement of the hummer produces a periodic variation in distance between sound source and listener, which leads to positive and negative frequency shifts due to the Doppler effect. This variation is related to the rotation period of the hummer.

3 METHODS

The measured (original sounds) and modelled data (synthesised) of the hummer instrument were provided by A. Hirschberg and are described in some detail in the following subsections. A more extensive description of the measurement set-up can be found in Hirschberg et al. [9].

3.1 Original sounds

The hummer was attached to a bicycle wheel and then recordings were made at different rotation speeds. Rotation speeds were controlled by an electrical motor. The set-up was installed in a semi-anechoic room with a volume of 100 m³.

The hummer was attached to the spikes of a 26" bicycle wheel. The inlet was fixed to the axis of rotation (wheel axis). The outlet was at a distance of 0.70 m from the wheel axis, approximately 0.30 m outside the radius of the wheel. The wheel was mounted on a horizontal aluminium tube with a 1-m squared cross section in such a way that the wheel was horizontally oriented, at a height of 2.23 m above the floor. The wheel axis was defined to be at coordinates (0,0,2.23) m.

A microphone B&K type 4190 was used to record the hummer rotating at different speeds. The microphone was located at coordinates (0.42, 0.72, 2.03) m. Each recording had a duration of 20 s and was sampled at 10 kHz, with an amplitude resolution of 16 bits. The rotation speed was chosen in order to produce a stable whistling tone. On average three recordings per mode were made, but only the most stable measurement was analysed (typically the last recording). The measured resonance frequencies differed by about 4% from the approximation given by Equation 1, as shown in Table 1. The waveforms of the measured signals in acoustic modes are shown in panels (a) and (b) of Figure 2.

The measured signals were re-sampled to 44.1 kHz, with an amplitude resolution of 16 bits. The average level was adjusted to 60 dB(A). The new sampling frequency of 44.1 Hz is required to ensure full compatibility with existing psychoacoustic models. All results obtained for frequencies above the Nyquist frequency of 5 kHz were ignored (corresponding to about 20 Bark). The one-third octave band spectra of acoustic modes 2 (left panel) and 5 (right panel) after calibration are shown in Figure 3.

3.2 Synthesised sounds

Considering a hummer of length $L = 0.7$ m as represented in Figure 1, the instrument can be modelled as two monopole sound sources. The inlet, near the axis of the wheel and having an entrance diameter of $D_{\text{ent}} = 3.3$ cm, was modelled as a fixed source S_1 , while the outlet was modelled as a rotating source S_2 with a rotation period of Ω_n . Because of the flexible nature of the hummer, an effective rotation radius R_{rot} of 0.67 m was used.

The synthesised waveforms were obtained using the model developed by Nakiboğlu et al. [8] and Hirschberg et al. [9], which accepts L , D_{ent} , R_{rot} , Ω_n , f_n and the parametrised positions $S_{1,2}(t)$ as input parameters. The measured resonance frequencies f_n and rotation periods Ω_n presented in Table 1 were used instead of the respective theoretical values. The obtained waveforms are shown in panels (c) and (d) of Figure 2.

The modelled signals at a sampling frequency of 44.1 kHz, with an amplitude resolution of 16 bits were adjusted to have an average level of 60 dB(A). The one-third octave band spectra of acoustic modes 2 (left panel) and 5 (right panel) after calibration are shown in Figure 3.

3.3 Evaluation criteria

In Figure 3 the spectra of measured and modelled signals are shown. The measured signals have broadband frequency components outside the range of resonance frequencies f_n , while for the synthesised sounds, the energy is concentrated on the band containing the resonance frequency. However, one-third octave band analysis techniques still correspond to the group of objective measures, and therefore, they do not take into account characteristics of sound perception. We have chosen psychoacoustic descriptors that account for level perception (loudness) and, to some extent, the pleasantness of sounds (roughness) to investigate whether there are significant perceptual

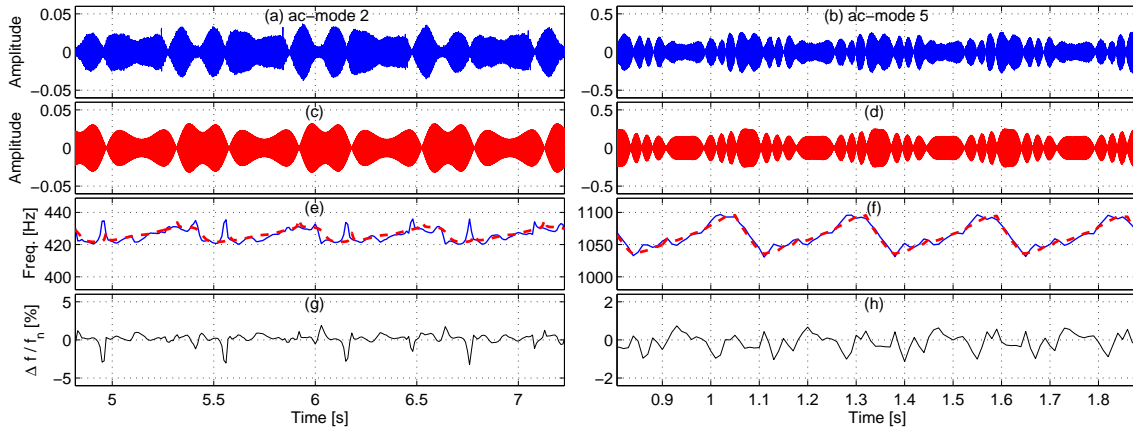


Figure 2: *Hummer*, acoustic modes 2 (left panel columns) and 5 (right panel columns). Top panels (a,b) and (c,d) show measured and modelled time signals, respectively. Panels (e) and (f) show fundamental frequency F_0 values estimated using the autocorrelation-based F_0 extractor available in Praat. Panels (g) and (h) show the differences [%] between F_0 values of the modelled relative to the measured signals.

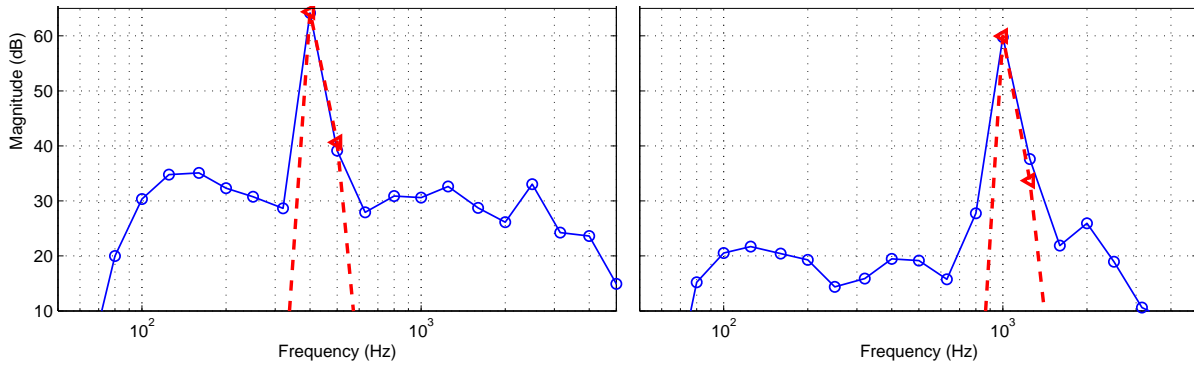


Figure 3: *One-third octave band spectra* for measured (circle markers) and modelled (triangle markers) *hummer* signals. The left and right panels show signals for acoustic modes 2 and 5, respectively. The level was set to 60 dB(A).

differences between measured and modelled signals. Furthermore, fundamental frequency contours were used to evaluate variation in frequency shifts of the *hummer* signals.

Psychoacoustic descriptors

Fundamental frequency (F0): corresponds to an estimate of the pitch periodicity of a sound and it is expressed in Hertz. A method used to estimate F0 values is based on the autocorrelation of a signal [10]. The implementation of this method in the Praat Analyser software was used¹ [11]. In this study, F0 estimates were used to investigate frequency variations of the *hummer* sounds. For sinusoidal frequency-modulated sounds (modulation frequency of 4 Hz) varying in $\pm\Delta f$ around a carrier frequency f , the just-noticeable threshold is $\Delta f = 1.8$ Hz up to $f = 500$ Hz and $\Delta f = 0.0035 \cdot f$ for carriers above 500 Hz [12]. Using these approximations, the just-

¹The frequency contours were obtained by using the following Praat command: To pitch (ac)... 0.01 75 15 no 0.01 0.45 0.01 0.35 0.14 1400.

noticeable changes in frequency of 0.4% ($f_2 = 424.4$ Hz) and 0.35% ($f_5 = 1061.7$ Hz) are obtained for acoustic modes 2 and 5, respectively.

Loudness: corresponds to the subjective correlate of the sound pressure level and it is expressed in sones. The reference sound producing 1 sone is a 1-kHz sine tone with an SPL of 40 dB. Loudness was evaluated using the so-called Dynamic Loudness Model DLM [13] which provides loudness excitation patterns in time and in frequency. In this paper we used the model outputs of main loudness (loudness as a function of time), average specific loudness (loudness as a function of frequency) and critical band levels related to the maximum (percentile 95) and minimum (percentile 5) specific loudness patterns.

Roughness (R): is a parameter that describes how “rough” a sound is. Roughness, which is produced by rapid amplitude (or frequency) modulations, reduces the pleasantness of sounds and noises [4, 12]. The sensation of roughness starts to appear from modulation frequencies of about 15 Hz up to 300 Hz and presents a bandpass characteristic with a maximum near a modulation frequency of 70 Hz. Roughness is expressed in asper, where a sound producing 1 asper corresponds to a 1-kHz sine tone, 100% amplitude-modulated, modulation frequency of 70 Hz and SPL of 60 dB. The model described by Daniel and Weber [4] was used. In this paper we used the model outputs of main roughness and specific roughness. The lower limit of roughness perception is 0.07 asper and several authors agree that a relative variation of about 17% elicits a just-noticeable change in roughness [4, 12, 14].

As shown in Table 1, all parameters were processed considering an analysis time of four periods of rotation, i.e., 2.4092 s and 1.0752 s for modes 2 and 5, respectively.

4 RESULTS

The results of the fundamental frequency estimation and the perceptual analysis using loudness and roughness for the hummer signals are presented in this section.

4.1 Fundamental frequency

The results for the fundamental frequency estimation are shown in panels (e) and (f) of Figure 2, where a pitch estimate was found for every audio segment (length of 40 ms, hop-size of 10 ms, F0 candidates between 75 and 1400 Hz). The normalised difference between measured and modelled F0 estimates are shown in panels (g) and (h) of the same Figure. The F0 estimates of the measured signals show a more rapid variation than those of the model signals. Additionally, the normalised differences exceed the just-noticeable variations in frequency reported in the literature for stationary frequency-modulated tones, with maximum absolute values of about 3% and 1% for acoustic modes 2 and 5, respectively. However, the evaluated sounds have modulations with dynamic variation (Doppler effect) rather than stationary modulations. This suggests that is unlikely to perceive these differences.

4.2 Loudness

The results for main loudness, average specific loudness and critical band levels using the Dynamic Loudness Model (DLM) are presented in Figures 4 and 5. As summarised in Table 2, original hummer signals showed a larger variability from period to period than the synthesised

sounds. In spite of this, it is possible to identify a periodic behaviour, which is clearer for acoustic mode 5 than for acoustic mode 2. Average specific loudness results are shown in panels (c) and (d) of Figure 4. As observed in the one-third octave band spectra in Figure 3, broadband frequency components were found for the measured signals, but having a larger loudness difference in acoustic mode 2 (ΔL_{50} of 1.37 sones), than in acoustic mode 5 (ΔL_{50} of 0.42 sones), compared to the synthesised sounds. Finally, results for maximum and minimum critical band levels are shown in Figure 5. The critical band levels of original and synthesised sounds show a good agreement in a frequency range of 5 to 6 Bark around the maximum.

Table 2: *Summary of main loudness as a function of time. Percentile 5 and 95 represent minimum and maximum values, respectively. Percentile 50 is an estimate of the mean loudness value. The overall roughness values are presented as well. The condition labelled as Measured* was obtained by applying a low-pass filter with cut-off frequency of 1300 Hz (10.2 Barks) and roll-off of 12 dB/octave to the measured signal, acoustic mode 2, resulting in a reduction in L_{50} of 0.88 sone and in R of 0.26 asper.*

Type	Acoustic mode	Loudness [sones]			Overall roughness [asper]
		L_5	L_{50}	L_{95}	
Measured	2	4.67 (± 0.07)	6.28 (± 0.12)	7.37 (± 0.16)	0.43
Modelled	2	3.00 (± 0.01)	4.91 (± 0.00)	6.13 (± 0.00)	0.02
Measured	5	3.55 (± 0.09)	3.96 (± 0.07)	4.81 (± 0.03)	0.26
Modelled	5	2.98 (± 0.01)	3.54 (± 0.00)	4.60 (± 0.02)	0.30
Measured*	2	3.81 (± 0.05)	5.40 (± 0.11)	6.53 (± 0.17)	0.17

4.3 Roughness

The results for average specific roughness are presented in Figure 6. In addition, overall roughness values (R) obtained by integrating the average specific curves along the critical-band rate are summarised in Table 2. The results show that roughness for the synthesised acoustic mode 2 (Figure 6, left panel) had a perceptual value below the roughness threshold of 0.07 asper, meaning that no roughness is perceived for the modelled signal. The measured signal had a total roughness of 0.43 asper, however this sensation was detected at frequencies above 10 Barks, being more prominent between 15 and 18 Barks, with a maximum around 17 Barks. By filtering this signal (low-pass filter, cut-off of 1300 Hz, roll-off of 12 dB/octave), roughness was reduced to 0.17 asper (60.4% reduction). Therefore, roughness can be attributed to the background noise present in the measured signal, which is not taken into account in the hummer model.

5 DISCUSSION

For measured signals of the hummer, variations in parameters that characterise each rotation period were expected, because the system was operated using a mechanical system. These variations were found in frequency ranges above the resonance frequencies of the acoustic modes. This suggests that they may be influenced by either (1) aerodynamic noise of the hummer, or (2) background noise of the mechanical system. On the contrary, synthesised signals were generated using constant model parameters (for each acoustic mode and every period) and therefore such differences were not expected here. Results for main loudness and average specific roughness, which are summarised in Table 2, were consistent with this idea.

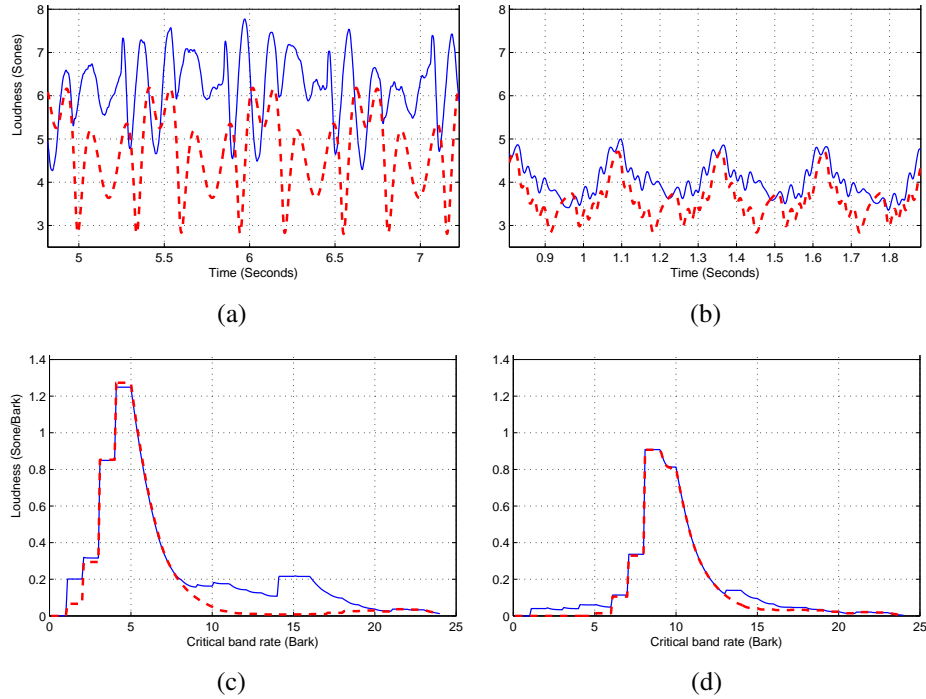


Figure 4: Loudness results for the hummer signals: Main loudness values as a function of time are shown in panels (a) and (b) for acoustic modes 2 and 5, respectively. Likewise, average specific loudness patterns as a function of frequency are shown in panels (c) and (d). Loudness differences between measured and modelled signals were approximately 1.47 and 0.50 sonas for acoustic modes 2 and 5, respectively. In both cases measured signals were louder.

5.1 Differences between original and synthesised sounds

A qualitative comparison of the hummer signals was presented by Nakiboğlu et al. [8] concluding that amplitude modulation depths were overestimated in the synthesised signals. That evaluation was made by comparing local minimum amplitude values of the waveforms (objective measure). However, based on the critical band levels shown in Figure 5, differences in modulation depth can be attributed to high frequency components of the measured signals and therefore it is unlikely that the hummer model overestimates (or underestimates) the depth of amplitude modulations. An additional condition was then taken into account, where the measured signal was low-pass filtered with a cut-off frequency of 1300 Hz (10.2 Barks) and roll-off of 12 dB/octave. This condition was labelled as Modelled* in Table 2. A reduction of 0.88 Bark was found, bringing the difference ΔL_{50} to 0.42 Bark.

The differences at high frequencies (above 11 Barks) were identified using both average specific loudness and average specific roughness. However, it is not possible to attribute them directly to the aerodynamic noise of the hummer or to the background noise (mechanical system or measurement room). If the background noise was related to aerodynamic noise of the hummer, further analyses need to be conducted to investigate how to include this effect in the hummer model. If the background noise is due to the operation of the mechanical system, measured signals can be filtered before being compared to modelled signals.

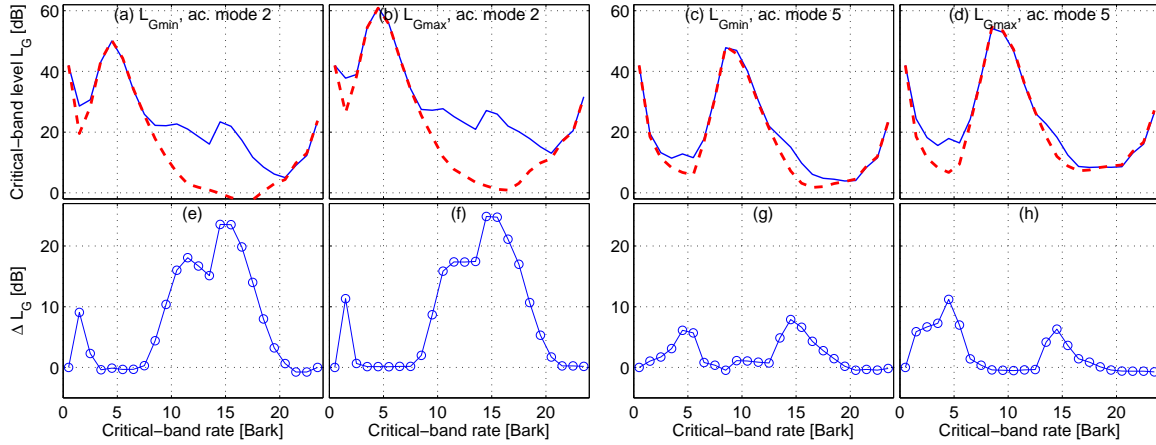


Figure 5: Critical band levels L_G [dB]. Minimum $L_{G,min}$ levels are shown in panels (a) and (c) for modes 2 and 5. Likewise, maximum $L_{G,max}$ levels are shown in panels (b) and (d). Below each panel, the differences between measured and modelled signals are shown. The differences of L_G were, within a range of $\|\Delta L_G\| < 3$ dB, from 2 to 8 Barks and from 7 to 13 Barks for acoustic modes 2 and 5, respectively.

5.2 Evaluation of musical instruments

A perceptual evaluation of the hummer has been presented based on the analysis of the psychoacoustic measures of loudness and roughness. To evaluate the applicability of these methods to other musical instruments it is important to keep in mind which characteristics of the hummer, as a musical instrument, have been addressed so far. The analyses presented in this study are based on the following aspects: (1) sounds were stationary; (2) sounds were harmonic complex tones; (3) sounds were evaluated in anechoic conditions. The stationary nature of the hummer allowed the application of a period-based analysis, nevertheless, it might be relevant to evaluate effects such as forward masking on auditory intensity discrimination, specially if temporal transients are present [see e.g., 15, 16]. For the hummer, the harmonic components and the periodicity of the signals allowed the use of average specific loudness and roughness to evaluate the signals. Additionally, pitch estimates were always found ($75 < F_0 < 1400$ Hz), therefore harmonic/non-harmonic and non-harmonic/harmonic transitions were not analysed. Furthermore, sounds in anechoic conditions were used, and thus the results presented in this paper do not take into account effects of the measurement room, e.g., reflections from any surface or total volume of the room. For the measurement of some instruments, it might be relevant to study these variables, for instance, when the perception of a listener in a concert hall is to be evaluated.

6 CONCLUSIONS

A perceptual evaluation of original and synthesised sounds of the hummer based on the psychoacoustic parameters of loudness and roughness was presented. The results showed that synthesised (modelled) sounds had a good agreement with original sounds around the resonance frequencies in the analysed acoustic modes and that it is unlikely that variations in frequency shifts are above a just-noticeable change in frequency. Additionally, masking patterns produced by the synthesised sounds using critical band levels, showed that modulation depths were properly modelled. However, background noise, which was partially masked in acoustic mode 5, was

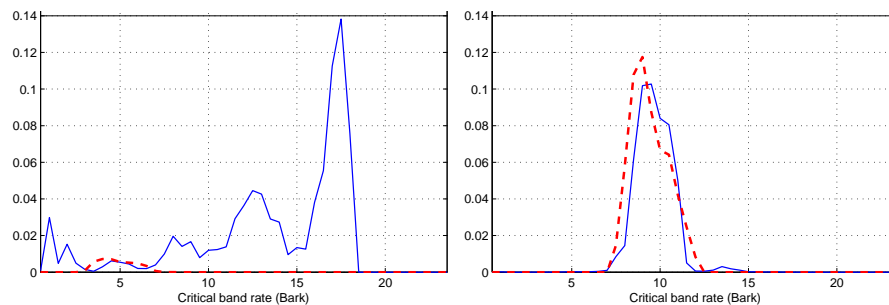


Figure 6: Averaged roughness R for the hummer signals. In the acoustic mode 2 (left panel), the measured signal showed a $R_{\text{meas}} = 0.37$ asper, while no roughness was found for the modelled signal ($R_{\text{model}} = 0.02$ asper, below the threshold of 0.07 asper). In the acoustic mode 5 (right panel) both, measured and modelled signals showed an average R value above threshold (0.26 and 0.30 asper, respectively). This difference of 0.04 asper is not perceptible, since this value is below the JND value.

not taken into account in the existing numerical model of the hummer and produced larger differences in both main loudness and roughness. The methods used to analyse the hummer, can be used for the analysis of other musical instruments, however, some aspects have not been addressed in this study: (1) influence of temporal transients; (2) transitions in pitch percepts from harmonic to non-harmonic and from non-harmonic to harmonic segments; (3) influences of room acoustic properties on the perception of instruments. To evaluate the influence of these aspects, other psychoacoustic measures might be needed. Another methods that may be applied are the use of temporal-varying models or molecular psychoacoustics to investigate, among others, the influence of temporal transients (forward masking). To account for the influences of the room characteristics, the method introduced in this study can be used to analyse measurements in semi-anechoic or reverberant conditions. In a first approach, auralisation techniques can be applied to the synthesised sounds to further compare the original and synthesised sounds.

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